AN EXTENSION OF THE VORTEX THEORY OF AIRSCREWS WITH APPLICATIONS TO AIRSCREWS OF SMALL PITCH, INCLUDING EXPERIMENTAL RESULTS.

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Summary.—The "vortex theory of airscrews" breaks down over a range of working conditions between zero advance and a certain speed of negative advance. It is suggested that in this range the axial inflow relation of the vortex theory should be replaced by an empirical relation to be obtained by analysing the performance of actual airscrews. To cover this gap in the theory a 2-bladed airscrew was tested having a pitch low enough to ensure that the angles of incidence of the blade section should not exceed stalling incidence.

The method of analysis and recalculation of performance is explained in general terms. The complete cycle of possible working conditions of an airscrew considered as an actuator disc is discussed on the assumption that the axial velocity through the disc is independent of radius, and with reference to the probable type of flow round the screw in each working condition. The performance of a single blade element of an airscrew of small pitch is then discussed in detail and it is found possible to describe in a general manner the cycle through which the element passes as the forward speed is varied continuously from a large positive to a large negative value while the rotational speed is kept constant.

Following the description of performance tests of the airscrews and aerofoil sections on which the calculations are based, the observed thrust curves of the two-bladed airscrew of aerofoils are analysed for four different values of the blade angle (+ 4°, 0°, − 2·6°, − 4°) on the assumption that the axial velocity is constant over the airscrew disc. Each airscrew provides a separate determination of the required empirical inflow curve; the results for the four screws are sufficiently consistent to support the initial assumptions and to enable a satisfactory mean curve to be drawn for all the screws. This curve is then used to recalculate the thrust and torque of the four screws and also of the 4-bladed airscrew of pitch diameter ratio 0·3 of the family of airscrews by a method which is identical with that of the vortex theory over the range in which that theory applies, the performance of the elements of different radii being calculated independently of each other. The agreement is satisfactory for the airscrews of aerofoils, and fair for the 4-bladed airscrew P/D 0·3 of the family of airscrews whose pitch ratio is greater than the largest effective pitch ratio of the airscrews used in the analysis.

The results have all been based on the observed wind tunnel velocity and apply to a 3-foot diameter airscrew working in a 7-foot square closed wind tunnel. The possibility of obtaining a correction to the velocity for tunnel interference is discussed with the help of a number of observations

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of velocity at different points in the tunnel with the airscrew running; a tentative correction is adopted, but in the region where the correction becomes large it is unreliable.

Conclusion.—The method of the present paper may be used with confidence to calculate the approximate performance of any airscrew whose pitch does not exceed the limits of the airscrews used in the analysis. For screws of higher pitch it is still the only method at present available over the range where the vortex theory breaks down.

NOTATION.

V = Forward velocity of airscrew, or tunnel velocity.
n = Rotational speed in revs. per second.
Ω = ,, ,, radians per second.
D = Diameter of airscrew.
R = Radius of airscrew.
ϕ = *See* § 3 (1) and Fig. 1 on p. 5.
r = Radius of an element.
a' = Rotational interference factor, *see* § 3 (1) and Fig. 1 on p. 5.
T = Total thrust of the airscrew.
Q = Total torque ,, ,, .
ρ = Air density.
$\left.\begin{array}{l} k_T = T/\rho n^2 D^4 \\ k_Q = Q/\rho n^2 D^5 \end{array}\right\}$ Thrust and torque coefficients for whole airscrew.
x = r/R.
u = Mean axial component velocity of the air through an element of the airscrew disc.
W = Resultant velocity past a section of the blade, and is defined by

$$u = W \sin \phi$$
$$r\Omega(1 - a') = W \cos \phi.$$

$$F = \frac{1}{4\pi\rho u^2 r} \frac{dT}{dr}.$$

$$f = \frac{1}{4\pi\rho V^2 r} \frac{dT}{dr}.$$

B = number of blades.
c = Chord of aerofoil section.
μ_1, μ_2 = *See* § 3 (1).

$$S = \frac{4\pi r}{Bc}.$$

θ = blade angle.
α = angle of incidence.

1. *Introduction.*—The object of the present paper is to show how certain of the formulæ of the "Vortex Theory of Airscrews"* can be extended to cover all possible working conditions of an airscrew; a method is suggested by which complete calculations for the most general case may be based on a single empirical

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* R. & M. 786: "An Aerodynamic Theory of the Airscrew," by H. Glauert.

curve (Figs. 2 and 3). A portion of this curve is based on the experiments of R. & M. 885* and covers the case where the velocity through the airscrew disc is small but in the same direction as the velocity at infinity. The remainder of the curve was obtained by analysing curves of thrust observed in the experiments described below, and afterwards the complete performance (thrust and torque) of each screw was recalculated by its means.

In devising experiments as a basis for extending the theory it is obvious that the multiplicity of possible screws and working conditions is so great that some principle of limitation is necessary. Accordingly the preliminary analysis and experiments have been confined to screws of small pitch.

The main advantage of this limitation appears to be that, as will be shown later (§ 5 (1)), the screw passes through all possible working conditions (as regards axial flow through the disc) without the angle of incidence of any section exceeding the stalling angle. Thus, the comparison between theory and experiment is not impaired by the additional complication of the stalling of the blade sections. It is also possible to obtain more general results and to simplify calculations when the blade angle and incidence are so small that cosine effects may be neglected. Accordingly, the two-bladed airscrew of aerofoils described in R. & M. 885† was chosen for the present purpose and was tested at a series of small blade angles.

2. *General Description of the Method of Analysis.*—The Vortex Theory of Airscrews is based on a clear distinction (in common with the Prandtl theory of aerofoils) between the actual fluid velocities in the immediate neighbourhood of the airscrew blades and the fictitious "interference velocities" which must be used in applying aerofoil data to strip theory calculations. In the development of the Vortex theory it is shown that the velocity field in a tubular region cutting the airscrew disc and bounded by radii r and $r + dr$ and by planes sufficiently close to the airscrew disc in front and behind, is completely determined by the angular velocity Ω of the screw (assuming zero rotation in the inflow‡) and the mean axial component velocity u relative to the airscrew disc through the annulus considered. The approximation should be close except in the immediate neighbourhood of the blade tips. The resultant forces on the blade elements can also be determined from these quantities and accordingly it is possible, on the basis of performance data for the aerofoil sections *reduced to infinite aspect ratio*, to calculate the resultant forces on the blade elements at radius r (*i.e.*, the elements of thrust dT and

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* R. & M. 885: "Some Experiments on Airscrews at Zero Torque," by C. N. H. Lock and H. Bateman.

† *Loc. cit.*

‡ This assumption may break down under extreme conditions. *See* appendix.

of torque dQ) in terms of Ω and u only. In practice it is convenient to assume values of Ω and the incidence α of the blade element at infinite aspect ratio, and to calculate values of u, $\frac{dT}{dr}$ and $\frac{dQ}{dr}$. The detailed formulæ are given below in § 3 (1).

In order to complete a calculation of airscrew performance it is necessary to determine a relation between the values of u at different radii and the velocity of advance V of the airscrew, a relation which presumably depends on the entire velocity field surrounding the screw. According to the Vortex theory, the tubular element consisting of fluid that has passed through the airscrew disc between radii r and $r + dr$ retains its identity (subject to certain limitations to the value of the thrust coefficient of the element) into the "wake" where the tube becomes cylindrical and the pressure is reduced to its atmospheric value. On the basis of this conception (which is similar to that of Froude), the value of the ratio u/V depends only on the thrust coefficient calculated on the basis of u

$$\frac{1}{4\pi\rho u^2 r} \cdot \frac{dT}{dr} = F \text{ say};$$

thus the different tubes of flow do not effect each other and the neighbouring elements are independent. According to the Vortex theory the relation between u/V and F takes the simple form

$$\frac{V}{u} = 1 - F^* \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2\cdot 0)$$

This relation should hold so long as the formation of a wake of normal type is possible. It is found to break down for sufficiently small values of u positive or negative; the exact limits of its applicability are discussed in R. & M. 869† and below.

In "Some Experiments on Airscrews at Zero Torque"‡ it was suggested that the Vortex theory might be modified to cover any working condition of any airscrew by replacing formula 2, p. 4, by an empirical formula for u/V in terms of F, to be obtained by analysing the performance of actual airscrews; this relation should agree with that of the Vortex theory over the range in which that theory applies. In practice it is convenient to represent this empirical relation by a curve connecting the variables $\frac{1}{f}$ and $\frac{1}{F}$ where the dependent variable f is defined by

$$f = \frac{1}{4\pi\rho V^2 r} \cdot \frac{dT}{dr} = \frac{u^2}{V^2} F$$

* Subject to certain sign conventions specified below in § 3·0, and § 4 (2).

† "Notes on the Vortex Theory of Airscrews." H. Glauert.

‡ R. & M. 885, *loc. cit.*

so that f and F are effectively the thrust coefficient of an element on the basis of the velocities V and u respectively. The advantage of this method of representation is that the variables only become infinite when the thrust is zero, *i.e.*, in a part of the working range where the Vortex theory is well established. This curve is plotted in Fig. 2, and on a smaller scale in Fig. 3, below.

We proceed to discuss in detail the method of obtaining and using this curve.

3. *Sign Conventions and Formulæ.*—In order to obtain equations which may be applied to any working condition of any airscrew it is necessary to specify the sign conventions to be adopted with more precision than is required if the formulæ are to be applied in the normal working range only. For any given airscrew (even if the blade section is symmetrical) one surface of the blade may be defined as the " under surface " and one edge as the leading

Flow at a Blade Element of a Normal Screw.

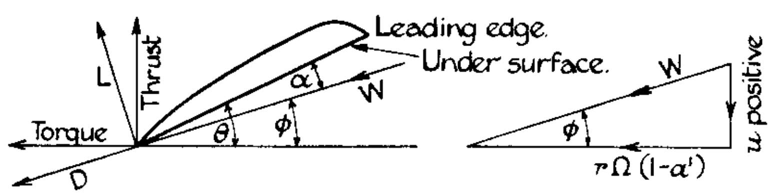

Fig. 1.

edge (*see* Fig. 1). The blade angle θ is defined as the angle lying between $\pm$ 90° through which the chord (or zero) line has rotated from the plane of the airscrew, and is reckoned positive when the leading edge moves towards the upper surface. The chord may be defined arbitrarily as any line fixed in the blade, and it may be sometimes convenient to choose it so that the lift vanishes with the incidence. Any axial velocity relative to the screw is positive when the flow is from the upper surface to the under surface, while an element of thrust is positive when the force on the screw acts from the under to the upper surface. An element of torque is positive when exerted by the air on the blade in a direction from leading to trailing edge, and a rotational velocity of the air relative to the screw is positive when its direction has the same sense. These definitions are consistent with the ordinary conventions for a normal airscrew. The lift and drag of a section are defined in the standard manner relative to the incidence, under surface, chord and leading edge. It is, of course, possible to define either surface as the under surface, but it is convenient to use the ordinary definition of under surface and leading edge for a section of normal type so as to avoid the necessity of modifying the aerofoil data.

(1) The following formulæ (equivalent to those of the Vortex theory*) are assumed to apply to an element of an airscrew under any working conditions :—

$$\frac{dk_T}{dx} = \pi^3 x^3 (1 - a')^2 \frac{\mu_1}{S}\dagger \quad \ldots\ldots \quad (3\cdot 11)$$

$$\frac{dk_Q}{dx} = \tfrac{1}{2}\pi^3 x^4 (1 - a')^2 \frac{\mu_2}{S}\dagger \quad \ldots\ldots \quad (3\cdot 12)$$

$$\mu_1 = \frac{k_L \cos\phi - k_D \sin\phi}{\cos^2\phi} \quad \ldots\ldots \quad \text{definition}$$

$$\mu_2 = \frac{k_D \cos\phi + k_L \sin\phi}{\cos^2\phi} \quad \ldots\ldots \quad \text{definition}$$

$$\frac{u}{nD} = \pi x \tan\phi\,(1 - a')\,\dagger \quad \ldots\ldots \quad (3\cdot 13)$$

$$F = \frac{1}{4\pi\rho u^2 r}\,\frac{dT}{dr} = \frac{\mu_1}{S\tan^2\phi} \quad \ldots\ldots \quad \text{definition}$$

$$f = \frac{1}{4\pi\rho V^2 r}\,\frac{dT}{dr} \quad \ldots\ldots \quad \text{definition}$$

$$\frac{1}{1 - a'} = 1 + \frac{\mu_2}{S\tan\phi}\dagger \quad \ldots\ldots \quad (3\cdot 14)$$

where

$k_T = T/\rho n^2 D^4$ - - - - - - definition

$k_Q = Q/\rho n^2 D^5$ - - - - - - definition

$x = r/R$ - - - - - - definition

$\phi = \theta - \alpha$ - - - - - - definition

$$S = \frac{4\pi r}{Bc}.$$

An (empirical) relation between f and F may then be used to complete the calculation of performance by using the alternative formulæ

$$V/nD = \pi x \tan\phi \,.\, \frac{V}{u} = \pi x \tan\phi \sqrt{\frac{F}{f}} \quad \ldots\ldots \quad (3\cdot 15)$$

or

$$V/nD = \pi x \sqrt{\frac{\mu_1}{Sf}} \quad \ldots\ldots \quad (3\cdot 16)$$

which can be deduced from equation (3·13) and the definitions.

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* *See also* R. & M. 892, p. 6. "The analysis of the results of the family of airscrews by means of the Vortex Theory." C. N. H. Lock and H. Bateman.

† Throughout the present report a' is assumed to be zero, the arguments for adopting this course being given in the appendix.

4. *The alternative assumption that the inflow velocity is constant over the airscrew disc.*—In the process of calculating the performance of an airscrew on the basis of the above formulæ together with the empirical curve connecting f and F (Fig. 2), the value of u is determined independently for each radius from its relation with V, so that the assumption that f is a function of F only involves the assumption of the independence of neighbouring elements of the airscrew disc. This seems to be the most natural method of extending the Vortex theory even though there is no evidence of the independence of neighbouring elements in extreme working conditions; this method has therefore been used in section 9·0 below in recalculating the performance of the screws on the basis of the mean empirical curve of Fig. 2.

On the other hand, in the converse process of deducing the empirical curve, the alternative assumption* that u = constant over the disc has been made so as to avoid impossible complications in analysing the experimental results. It is then a simple matter to calculate k_T and k_Q as functions of the constant u/nD from the formula of § 3·0 only; it is then obvious that the variable

$$f = \frac{1}{4\pi\rho V^2 r} \frac{dT}{dr}$$

cannot in general be a function of

$$F = \frac{1}{4\pi\rho u^2 r} \frac{dT}{dr}$$

only, since u and V are now both independent of r. Consequently these variables are replaced by their mean values over the airscrew disc defined by the equations

$$\bar{f} = \frac{1}{4\pi\rho V^2} \quad \frac{\int_o^R dT}{\int_o^R r\,dr} = \frac{T}{2\pi\rho R^2 V^2}$$

$$\bar{F} = \frac{1}{4\pi\rho u^2} \quad \frac{\int_o^R dT}{\int_o^R r\,dr} = \frac{T}{2\pi\rho R^2 u^2}$$

Of these variables, $\bar{F}$ is completely determinable by calculation, and $\bar{f}$ by experiment; to complete the process of analysis it is therefore only necessary to plot these variables as in Fig. 2.

This curve is used in recalculating the performance of any screw on the assumption that the same relation between $\frac{1}{\bar{f}}$ and $\frac{1}{\bar{F}}$ exists when the elements are independent as when u is constant; this would be exactly true if both F and u happened to be inde-

* This assumption was suggested by Mr. Glauert in T. 2236. "The Analysis of Experimental Results in the Windmill Brake and Vortex Ring States of an Airscrew." (Unpublished.)

pendent of r when the elements were assumed independent since we should then have

$$f = \bar{f}, \quad F = \bar{F}.$$

The smallness of the error involved in practice may be verified from the accuracy of the agreement of the recalculated thrust curves with the original observed thrust curves from which Fig. 2 was obtained. It is worth noting that both u and F are independent of r for the particular case of a screw of constant (small) geometrical pitch, with chord and section of blades independent of radius, and the lift of the section proportional to the angle of incidence.

The assumption of u constant is also convenient as a basis for the following discussion of the probable types of flow corresponding to the different working states of an airscrew, since it is then possible to consider the working state of the whole screw instead of an element.

(1.) *Discussion of different types of flow neglecting rotational effects and assuming u constant over disc.*—In Fig. 4 are sketched the probable types of flow obtaining in the various working conditions; the corresponding points on the standard curve of Fig. 3 are distinguished by the same letters. We proceed to show how a continuous variation of the thrust and axial inflow velocity corresponds to a single passage along the complete curve of Fig. 3.

In this discussion the screw is regarded solely as an actuator disc capable of producing thrust and axial velocity, and it is not implied that the cycle of changes in T, u and V through which it will be taken could be completely realised for a particular screw by variation of V and n only, without a progressive modification of the screw itself.

Consider the screw working under such conditions that the thrust is zero. Then on all theories $u/V = 1, f = F = 0$, Figs. 3 and 4, (b). Assume u and V positive, and suppose that the conditions are so altered as to make the thrust positive; u/V becomes greater than unity and we have the " normal working state " (N) in which u/V increases indefinitely until we reach the static condition at which V becomes zero, so that $\frac{1}{f}$ becomes zero while $\frac{1}{F}$ attains a finite limit which probably lies between 1.0 and 2.0; Figs. 3 and 4, (a).

Starting from zero thrust in the opposite direction the thrust becomes negative and u/V becomes less than unity. We shall refer to this as the " windmill brake state " (W), Fig. 2 and Figs. 3 and 4, (c and d) up to the limit at which u vanishes and hence $\frac{1}{F}$ vanishes. It appears that the Vortex theory breaks down at

$\frac{1}{F} = -1$, ($u/V = \frac{1}{2}$ by formula 2.0) since the area of the assumed "wake" becomes infinite. For $\frac{1}{F}$ less than -1 it is probable that a vortex ring or turbulent region is formed behind the screw Figs. 3 and 4, (d). This will be distinguished when necessary as the turbulent "windmill brake state." Proceeding beyond the limit of this state u vanishes and becomes negative while $\frac{1}{F}$ vanishes but does not change sign, remaining negative. At the point of vanishing of u, V in general does not vanish so that $\frac{1}{f}$ has a finite limit. Beyond this point, u becomes negative and the vortex ring embraces the screw; Figs. 3 and 4, (e); this condition will be called the "Vortex ring state" (V).* At the end of the vortex ring state V vanishes and changes sign giving the static condition with the sign of all quantities changed, u and F both being negative; Figs. 3 and 4, (f and a_1). It is therefore necessary to apply a process similar to the first but with the signs of all quantities changed in order to complete the cycle and return to the starting point. The corresponding points in Fig. 3 are marked as (b_1) . . . . . . (f_1).

(2.) *Resolution of ambiguities.*—In general $1/f$ is a two-valued function of $1/F$ (*see* Fig. 2) one value corresponding to the windmill brake state (W), and the other to the normal working state (N) and vortex ring state (V). To resolve the ambiguity it is sufficient to notice that the condition that u and μ_1 (or dT) are of the same *sign* (u being of opposite *sense* to the element of thrust according to the sign conventions of section 3) corresponds to the working conditions (N) and (V); the former or latter condition is indicated according as $1/F$ is $>$ or $<$ its value for $\frac{1}{f} = 0$; u and μ_1 of opposite sign corresponds to the condition (W). The sign of μ_1 is always known in terms of θ and a; the sign of u is known from formula 3.13

$$\frac{u}{nD} = \pi x \tan \phi$$

if the sign of n is known, and in general it may be assumed that

$$n \text{ is positive if } -90^\circ < a < 90^\circ$$
$$n \text{ is negative if } 90^\circ < a < 270^\circ$$

according to the conventions of page 6.

* The idea of this classification of working states is due to De Bothesat ("The General Theory of Blade Screws," N.A.C.A. Reports No. 29), but the definitions here adopted are different from his.

TABLE FOR RESOLVING THE AMBIGUITY IN THE USE OF FIG. 2 TO DETERMINE $1/f$ FROM $1/F$.

The letters denote working states—

N = Normal working state.
V = Vortex ring state.
W = Windmill brake state.

$\mu_1 \downarrow$ \ $\tan\phi \rightarrow$	n positive: +	n positive: −	n negative: +	n negative: −
+	N, V	W	W	N, V
−	W	N, V	N, V	W

Finally the ambiguity of sign of V/nD can be resolved by the consideration that V is of the same sign as u throughout the states (N) and (W) and of opposite sign in state (V).

The ordinary formulæ of the Vortex theory apply to the case in which u is positive. If the sign of u and μ_1 are both changed, the signs of f and F are changed but the relation between u and V is unaltered, hence the formula

$$\frac{F}{f} = (1 - F)^2,$$

which can be deduced from equation (2.0) above for u, is replaced by

$$\frac{F}{f} = (1 + F)^2$$

when u is negative.

Having discussed the general nature of the types of flow in the different possible working conditions of any airscrew treated as an actuator disc on the assumption of constant inflow over the disc, it is now necessary to consider in greater detail the variation of the performance of a single element of an airscrew of low pitch in passing from a large positive to a large negative value of V/nD (n being positive throughout).

5. *The airscrew of small pitch.*—Take a single section of an airscrew (at a radius 0·75R, say) of which the angle of pitch (or blade angle) as defined above is small; and consider in a general manner the variation of thrust and inflow in passing from a moderate negative to a moderate positive value of V, keeping the value of n constant and positive throughout.

The general formulæ are simplified as follows :—neglect the profile drag in calculating thrust and inflow and assume that the lift of the element is proportional to the incidence α_1, measured from the no-lift angle, so that $k_L = p\alpha_1$; neglect squares of α, θ and ϕ; neglect rotational interference.* In this way the general formulæ are reduced to a simplified form as follow :—

General formulæ —become— simplified formulæ.

$$F = \frac{\mu_1}{S \tan^2\phi} \qquad\qquad F = \frac{p\alpha_1}{S(\theta - \alpha_1)^2}$$

$$\frac{dk_T}{dx} = \pi^3 x^3 \frac{1}{S}(1 - a')^2 \mu_1 \qquad\qquad \frac{dk_T}{dx} = \frac{\pi^3 x^3 p\alpha_1}{S}$$

$$V/nD = \pi x \lambda$$

$$\lambda^2 = \tan^2\phi \frac{F}{f} \qquad\qquad \lambda^2 = (\theta - \alpha_1)^2 \frac{F}{f}$$

or

$$\lambda^2 = \frac{\mu_1}{Sf} \qquad\qquad \lambda^2 = \frac{p\alpha_1}{Sf}$$

and f is to be determined as a function of F from the curve of Figs. 2 and 3 using the conventions of Section 4(1) above. Curves have been calculated by these formulæ to illustrate the following remarks, and are shown in Fig. 5.

Considering first the case of a positive blade angle θ, we start with zero thrust for which $\alpha_1 = o$ (n positive); then $\phi = \theta$ and is positive, and u is positive (formula (3·13)). Hence, when α_1 is small and negative, μ_1 ($= p\alpha_1$) is negative, and it follows from the argument of § 4 (2) that the airscrew is working in the windmill brake state, F & f being negative. Also V is positive and so λ is positive. As $-\alpha_1$ increases as far as the stalling angle, neither $1/F$ nor dT/dr vanish and hence the state of the airscrew does not alter. It is important to notice that the expression

$$-F = \frac{-p\alpha_1}{S(\theta - \alpha_1)^2}$$

reaches the maximum value $p/4S\theta$ in the range of α_1 negative so that $-1/F$ has the minimum value $4S\theta/p$ corresponding to $\alpha_1 = -\theta$. *See* Fig. 5, especially the curves for $\theta = 3°$.

For small positive values of α_1, the airscrew is in the normal working state until V and λ vanish and change sign, which can be shown from the formulæ to occur when $1/F = 2.0$ according to the curve of Fig. 2, and this occurs for some value of α_1 between 0 and θ since F assumes every positive value as α_1 varies between these limits.

From this point we have the vortex ring state until $\alpha_1 = \theta$ when ϕ, u and $1/F$ all vanish and the airscrew passes to the windmill

* The rotational interference is neglected in all the calculations of the present paper. The arguments for adopting this course are given in the appendix.

brake state with F and f positive and V and λ negative. This condition then persists indefinitely since $1/F$ continuously increases with α_1.

(l). We proceed to summarise the changes corresponding to a continuous change of α_1 from a large negative to a large positive value.

State.	Critical condition.	
Windmill brake (W).		V and λ large positive; α_1 large negative; windmill brake state with $1/F$ and $1/f$ large and negative; $-1/F$ decreasing with V.
	(1)	$-1/F$ reaches the minimum value $4S\theta/p$ for $\alpha_1 = -\theta$.
Windmill brake (W).		Same working state with $-1/F$ increasing indefinitely.
	(2)	α_1 vanishes; thrust zero; F vanishes and changes sign.
Normal (N).		Normal working state; $1/F$ positive and decreasing until :—
	(3)	V and λ vanish and change sign, for a value α_0 of α_1 between 0 and θ_2.
Vortex ring (V)		Vortex ring state with V and λ negative and u positive, and $1/F$ positive.
	(4)	$\alpha_1 = \theta$; ϕ vanishes; $1/F$ vanishes but does not change sign; u vanishes and changes sign.
Windmill brake (W).		V and λ large and negative; α_1 large positive; $1/F$ and $1/f$ positive and increasing indefinitely.

Reference should be made to Fig. 5 for illustration of the above remarks; the corresponding results for θ negative can easily be deduced from the figure.

It appears that between the critical conditions marked (1) and (4) the airscrew has passed through all possible ranges (*i.e.*, all relations between F and f) except for the portion of the windmill brake state included between $1/F = 0$ and $1/F = -4S\theta/p$.

As θ decreases, the value of the last quantity tends to zero and at the same time the range of values of α_1 and λ included between the critical conditions (1) and (4), *i.e.*, between $\alpha_1 = -\theta$ and $\alpha_1 = \theta$, also tends to zero.

Thus in the limiting case of a section of zero pitch the whole of the range from the first to the fourth critical point disappears and the screw passes abruptly from the condition V small negative, u/V small positive, to the condition V small positive, u/V small positive, for constant rotational speed. As a corollary it follows that the windmill brake state is the only possible condition for a screw of zero pitch.

It has been assumed that V/nD increases continuously as a_1 decreases throughout the entire range. This is the fact in practice with the curve of Fig. 2 in all the cases for which calculations were made.

6. *Experimental details.*—The principal tests here described were made on the two-bladed airscrew of aerofoils (diameter 3 ft. chord 2·5 ins.) described in R. & M. 885* (one of the blades having been re-made identical with the other) with the blades set at 4°, 0° and — 4°. The dimensions of the blade section are recorded in Table 9. A few readings were also taken with blades set at — 2·6° which was found by trial to give zero thrust in the static condition. Accordingly the above settings correspond to blade angles measured from the no lift angle of about $6\frac{1}{2}$°, $2\frac{1}{2}$°, — $1\frac{1}{2}$° respectively.

The screws were tested over a large range of V/nD with V both positive and negative, the angular velocity being positive (leading edge forward) throughout. The negative V/nD range, as embracing small positive values of incidence, secured the greatest attention.

One screw of the Family of Airscrews (4-bladed airscrew No. 1 of P/D 0.3)† was tested over a range of positive and negative V/nD with n positive.

The experiments were carried out in the No. 1 7 ft. tunnel by the standard methods described in R. & M. 829†, except that the airscrew balance was modified for use with the 3-phase induction motor described in R. & M. 778‡. The motor was supported by a single steel point forward, at the junction of a pair of stranded cables suspended from shackles connected to the roof and forming a V in a plane across the tunnel. A second point aft was supported by the upper end of the main bottom balance spindle, the drag beam of which was employed to measure thrust, the airscrew motor moving fore and aft with the motion of the balance. The motor was free to rock about a line passing through the two supporting points slightly above the airscrew axis, and the torque was measured through an arm projecting from the side of the motor, connected by a vertical wire to a small weigh beam on the roof of the tunnel.

By the use of the 3-phase induction motor the steadiness of running was considerably improved, especially when the working range included a considerable negative torque, which merely caused the airscrew to run at a speed slightly higher than that of the generator.

In order to test the screw at low values of V/nD, special arrangements were made to run the tunnel steadily at very low speeds, by connecting the armature of the tunnel motor

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* "Some Experiments with Airscrews at Zero Torque," by C. N. H. Lock and H. Bateman.

† R. & M. 829: "Experiments with a Family of Airscrews. Part I."

‡ "An Electric Motor of Small Diameter for Use inside Aeroplane Models." E. F. Relf.

to a battery supply at a lower voltage while keeping the field on the normal voltage. In this way a tunnel speed of 5 ft./sec. and a V/nD of 0·07 was obtained.

For reasons explained below, the observed velocity was not corrected for wind tunnel interference; otherwise the experimental results were worked out exactly as described in R. & M. 829.* The correction for the resistance of the supporting wires was found to be negligible; the resistance of the large metal boss was included in the calculated thrust so that both observations and calculations refer to the airscrew with large boss, although the relative importance of the boss resistance is small.

The values of k_T, k_Q and V/nD are recorded in Tables 3 and 4 and plotted in Figs. 6, 7, 8 and 9.

Some additional data are available for the airscrew of aerofoils at some other blade angles but only refer to the screw rotating as a windmill on ball bearings at zero torque. At blade angles $-6°$, $-3°$, $-1°$, $-0·5°$, results are available from R. & M. 885. The results given in that report include a correction for tunnel interference which is of doubtful validity; accordingly the results of the original experiments are given here in Table 5a on the basis of observed tunnel velocity. At blade angles $-4°$, $-2°$, $0°$, $+1°$ the airscrew has been tested at zero torque at various angles to the wind. The results have not yet been published, but the results for the airscrew normal to the wind are quoted here in Table 5a.

(1). *Aerofoil data.*—The section of the Airscrew of Aerofoils (Table 9) was re-tested for the present experiment through a range of 360° at 40 ft./sec. and over a small range at 60 and 70 ft./sec. The results reduced to infinite aspect ratio are recorded in Table 1.

Owing to the necessarily low scale of these tests (the actual blades of the airscrew being used), it was decided (as in R. & M. 885) to extrapolate to a high scale for angles of incidence below the stall. The aerofoil tests at 40, 60 and 70 ft./sec. on a chord of 2·5 inches correspond to VL 8·3, 12·4, 14·5; the results below the stall were extrapolated to $VL = 30$, corresponding to the velocity of a section of the airscrew at $0·75\,R$ when running at about 20 revolutions per second, which is the average speed at which the screw was tested (*see* Table 3). In making the extrapolation the results of tests of a R.A.F. 6A aerofoil at values of VL of 5, 10, 15, 20, 25 and 30, described in R. & M. 148† were used as a guide. The results for the drag were fairly definite and agreed with those in R. & M. 885. In that report, however, the scale effect on lift was neglected, while from the results of R. & M. 148 there appeared to be a considerable scale effect near zero lift. Also the fact that a screw of blade

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* "Experiments with a Family of Airscrews. Part I."

† "Experiments on the Variation of the Lift and Drag Coefficients of an Aerofoil as the Speed changes." Bairstow, Pannell and Lavender. R. & M. 148, 1914–15 Year Book.

angle $-2 \cdot 6°$ gave zero thrust at static indicated that $-2 \cdot 6°$ was the no-lift angle for an element of the screw, whereas the no-lift angle at 70 ft./sec. is $-2 \cdot 1°$. The results of R. & M. 148 were consistent with a decrease of no-lift angle from $-2 \cdot 1°$ to $-2 \cdot 6°$ between VL 14 and VL 30; accordingly the latter value was accepted for the no-lift angle. Finally, above the stall the results at 40 ft./sec. were used. The final values used in the calculations are given in Table 2.

7. *Discussion of results.*—The thrust curves of Fig. 6 show no indication that the screw passes through any very critical condition within the range covered by the tests; the curves for the different screws are to a first approximation parallel to each other, but the thrust at static is approximately proportional to the square of the blade angle in accordance with theory. The chief interest in the torque curves (Figs. 7 and 8) lies in the large region of negative torque for the screws of blade angle $-4°$ and 0° at negative V/nD. Even the screw of blade angle $+4°$ shows a small region of negative torque in the neighbourhood of $V/nD - 0 \cdot 5$ (*i.e.*, with the leading edge of the blade pointing away from the wind). Calculation also indicates a small range of negative torque for each section of this screw. The torque in this region also shows a very large scale effect; an attempt has been made in Figs. 7 and 8 to draw separate approximate curves for different rotational speeds through the observed points. With the blades at $+4°$ the torque only becomes negative for a tunnel speed greater than about 10 ft./sec. corresponding to a rotational speed of $8 \cdot 3$ revolutions per sec. To verify this fact, the screw was run up to an appropriate angular velocity at a high tunnel speed, and then allowed to run freely by cutting off the supply of power. On reducing the tunnel speed gradually, the screw continued to rotate at approximately the same V/nD ($-0 \cdot 40$) until at a tunnel speed of 10 ft./sec. the screw stopped.

The condition of zero torque at the smaller absolute values of negative V/nD corresponds with the conditions of the tests at zero torque of the same airscrew in R. & M. 885 and elsewhere, recorded in Table 5a. These additional results are plotted (as single points) in Figs. 6 and 8. Fig. 6 shows that the two sets of experiments (viz., on ball bearings and with motor) are in good agreement on thrust, but there is an appreciable discrepancy on torque. To remove the discrepancy it would be necessary to assume a friction couple of about $0 \cdot 5$ lbs. ins. at 20 revs. per second, for the ball bearing, which is surprisingly large.

The results for the 4-bladed airscrew No. 1 of the family of airscrews are shown in Fig. 9. The general form of the thrust and torque curves is similar to those of Figs. 6 and 7, but the torque does not become negative for negative V/nD. The only point calling for remark is the extreme unsteadiness of the readings in the neighbourhood of $V/nD - 1 \cdot 0$. It seems probable that this was due to the stalling of some of the blade sections.

8. *Analysis of experimental results.*—The observed values of the thrust coefficients k_T shown in Fig. 6 were analysed by the method described in § 4 above, *i.e.*, on the assumption that the axial inflow velocity u is constant over the airscrew disc. By this method curves of k_T against u/nD were calculated and compared with the smoothed curves of observed k_T against V/nD, corrected for boss effect, and a series of corresponding values of $1/\bar{f}$, $1/\bar{F}$ obtained, where

$$\bar{f} = \frac{T}{2\pi\rho V^2 D^2} = \frac{2}{\pi}\frac{k_T}{(V/nD)^2} \quad \cdots\cdots\cdots\cdots \quad (8\cdot 01)$$

$$\bar{F} = \frac{T}{2\pi\rho u^2 D^2} = \frac{2}{\pi}\frac{k_T}{(u/nD)^2} \quad \cdots\cdots\cdots\cdots \quad (8\cdot 02)$$

A series of points covering all the observations on the four screws (blade angles $-4°$, $-2\cdot 6°$, $0°$, $4°$) are plotted in Fig. 2. Additional points are derived from the single observations at zero torque for the same screws set at blade angles $-3°$, $-2°$, $-1°$, $-\frac{1}{2}°$, $+1°$.

The results for the different screws are sufficiently consistent to permit the drawing of a fairly satisfactory mean curve through the points. The smoothed values obtained from this curve are recorded in Table 7. In drawing this curve results near and above the stalling angle of the sections are neglected, and greater weight is given to points corresponding to fairly large values of k_T. Thus the curve in the vortex ring state is based almost exclusively on the screw at $+4°$. For large values of $\frac{1}{\bar{f}}$ and $\frac{1}{\bar{F}}$ the following approximation to the Vortex theory is used

$$\frac{1}{\bar{f}} = \frac{1}{\bar{F}} \mp 2$$

the upper or lower sign being used according as u is positive or negative (*see* § 4(2)). The smooth curve is shown over a larger range in Fig. 3.

9. *Recalculation of performance and comparison with experiments.*—Using the mean curve of Figs. 2 and 3 the thrust and torque coefficients against V/nD were recalculated by the method of § 3(1), *i.e.*, assuming the elements at different radii to be independent. Both in the analysis and recalculation values of $\frac{dk_T}{dx}$ and $\frac{dk_Q}{dx}$ were calculated for radii $0\cdot 4R$, $0\cdot 6R$, $0\cdot 75R$, $0\cdot 9R$. From $0\cdot 9R$ to the tip the thrust and torque curves were brought down smoothly to zero by eye, so as to make a rough allowance for tip loss. (The blades of the airscrew were rounded off from radius $0\cdot 91R$ to the tip). The thrust curves were also brought down abruptly to zero at a radius $0\cdot 165R$ corresponding to the

inner end of the blades. A correction for the resistance of the boss (the large boss of the family of airscrews) was applied to the calculated value of k_T. This correction was taken as $0 \cdot 0066\ (u/nD)^2$. For the recalculation the approximate mean value of u at the airscrew disc was used, the correction being usually of small importance.

The calculated values are compared with observation in Fig. 6 for thrust and Figs. 7 and 8 for torque. Complete calculations were made for blade angles $-4°$, $-2 \cdot 6°$, $0°$, $4°$ and results were interpolated for $-3°$, $-2°$, $-1°$, $-0 \cdot 5°$, $+1°$ for comparison with the additional data of Table 5a. Since the thrust was recalculated on the basis of the curve of Fig. 2 which was obtained by an analysis of the same thrust, the agreement shown in Fig. 6 merely verifies the fact that the points of Fig. 2 lie fairly well on the smooth curve, and that the neglect of variations of u with radius in the analysis does not seriously affect the results. On the other hand, the good agreement on torque shown in Figs. 7 and 8 is a valuable confirmation of the correctness of the initial assumptions. The curves would be brought into still better agreement if a larger allowance were made for tip loss.

Beyond the stall the experimental and theoretical curves begin to diverge seriously, but since the aerofoil tests were not taken at a sufficiently large scale this region has been ignored.

Finally the performance of 4-bladed airscrew No. 1 was calculated by the method of section 3(1), using the mean curve of Figs. 2 and 3 on the basis of aerofoil data given in R. & M. 892*, Table 3 (Higher wind speed), and the results are compared with observations in Fig. 9. This is a fairly severe test of the assumptions, since the blade angle at a radius $0 \cdot 75R$ is $7\frac{1}{4}°$. The agreement is fairly satisfactory, and the worst discrepancy occurs in the neighbourhood of the static condition. It may be noticed that near static there are three different values of V/nD corresponding to a single value of k_T, a feature which also occurs for the airscrew of aerofoils set at $+4°$. This feature would require a loop in the curve of Fig. 2, which would cause difficulty in the calculations. For this reason the mean curve of Fig. 2 was drawn with a sharp bend at $\frac{1}{f} = 0$ in place of a loop.

(1). *Details of method of calculation.*—Details of the method of analysis and recalculation are collected here for convenience of reference and illustrated by a specimen calculation given in Table 6 which refers to the airscrew of aerofoils with blade angle $+4°$ (measured from the chord).

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* *Loc. cit.* The discrepancy between the calculated values of k_T and k_Q for positive V/nD in the present report and in R. & M. 892, is due partly to the neglect of rotational interference in the present report and partly to the difference between the standard curve of Figs. 2 & 3 and the formula of the Vortex Theory.

Analysis.—Select a range of values of the incidence α (in the present instance this should include all angles below the stall). The data required are the values of k_L and k_D reduced to infinite aspect ratio for a series of sections at different radii (Table 2), and the blade angle θ. Calculate μ_1 and μ_2 for each α and x by formulæ of 3·1 (columns 1 to 6 of Table 6). In the present case the blade section and angle θ are independent of radius, so that one calculation serves for all values of x up to this point.

For a series of radii (*e.g.*, $x = 0{\cdot}4R$, $0{\cdot}6R$, $0{\cdot}75R$, $0{\cdot}90R$) calculate u/nD, dk_T/dx by formulæ (3.11), (3.12), (3.13) (columns 7, 8 and 9). Cross plot dk_T/dx against u/nD for each value of x and read off for equal intervals of u/nD (columns 10 and 11). Plot dk_T/dx against x for each u/nD and integrate graphically to obtain k_T; subtract boss correction to obtain corrected k_T (*see* § 9). From smoothed curves of observed k_T against V/nD read off values of V/nD corresponding to calculated k_T (column 15). Calculate $1/\overline{F}$ and $1/\overline{f}$ by formulæ (8·01), (8.02) and plot (*i.e.*, Fig. 2). After all screws had been analysed a smooth curve was drawn (Figs. 2 and 3 and Table 7).

(2). *Recalculation.*—(Columns 1 to 6, 8 and 9 of Table 6 are to be used again). For each α and x calculate $1/F$ by formula of § 3(1) :—

$$F = \mu_1/S \tan^2\phi$$

Read off corresponding value of $1/f$, with due regard to the conventions of § 4(2), from smooth curve (Table 7). Calculate V/nD by formula (3.15) or (3.16). (First formula applies unless ϕ is small and second applies unless μ_1 is small.) (Columns 18–21). Cross plot dk_T/dx (from column 8) against V/nD from column 21, plot against x for even values of V/nD and integrate graphically to obtain k_T. Treat dk_Q/dx in a similar manner to obtain k_Q.

10. *The correction of the wind speed for the interference of the tunnel walls on the airscrew.*—It was realised at the outset of these experiments that the flow past a 3-foot airscrew in a 7-foot wind tunnel would differ from the corresponding free air flow in an especially marked degree in the extreme working states (turbulent windmill-brake state and vortex ring state), while there exist at present no reliable experimental data on which to base a correction. In particular it is considered that the method of correction tentatively used in R. & M. 885 is unsound, and probably overestimates the value of the correction, while in any case it does not apply to the vortex ring state.

For this reason all the results recorded up to this point are based on the velocity measured on the tunnel gauge, which was connected to a hole in the side of the tunnel 8 ft. forward of the airscrew, and represents the mean velocity in this plane to a sufficient approximation in all cases. This course seems to be justified by the fact that if a reliable method of correction should become available it can be applied directly (to a sufficient approximation) both to the observations as a correction on V/nD, and to the curve of $1/f$ against $1/F$ in Figs. 2 and 3 as a correction on the value of V occurring in f as defined by the equation

$$f = \frac{T}{2\pi\rho R^2 V^2}.$$

Accordingly the results of the present paper must wait for further experimental data before they can be applied exactly to an airscrew working in free air.

It seems worth while, however, to give the results of applying a certain approximate method of correction which, while it lacks experimental verification, seems likely to lead to results which are at least nearer the free air condition than are the uncorrected results. This method consists in adopting the mean velocity in the plane of the airscrew disc outside it as the equivalent free air speed, and has the advantage that the correction can be easily calculated when the relation shown in Fig. 2 is known for the wind tunnel, by the following application of the condition of continuity of the flow in the wind tunnel.

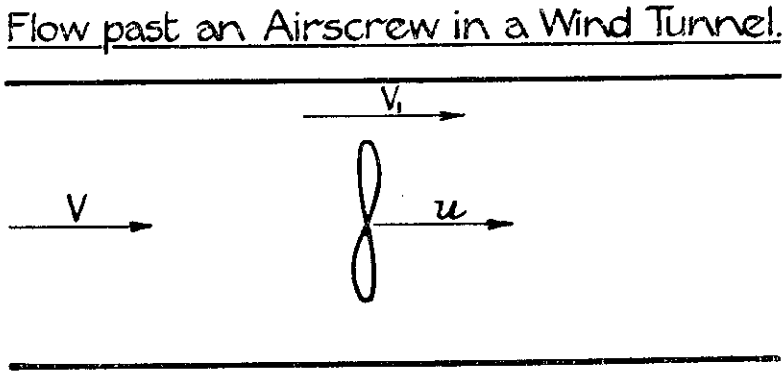

FIG. 11.

Referring to Fig. 11 for the definition of the tunnel velocity V, the velocity through the airscrew disc u, and the mean velocity V_1 in the plane of the airscrew outside it, and writing

$$F = \frac{T}{2\pi\rho R^2 u^2}$$

$$f = \frac{T}{2\pi\rho R^2 V^2}$$

$$f_1 = \frac{T}{2\pi\rho R^2 V^2_1}$$

it follows that if z is the ratio of disc area of airscrew to tunnel area

$$\frac{V_1}{V} = \left(\frac{f}{f_1}\right)^{\frac{1}{2}}$$

$$= 1 + \frac{z}{1-z}\left\{1 - \frac{u}{V}\right\}$$

$$= 1 + \frac{z}{1-z}\left\{1 \mp \left(\frac{f}{F}\right)^{\frac{1}{2}}\right\} \quad \text{........} \quad (10\cdot 01)$$

where the upper sign is taken except when u/V is negative, *e.g.*, for vortex ring state.

The value of f_1 determined by this formula is plotted $\left(\frac{1}{f_1} \text{ against } \frac{1}{F}\right)$ as the dotted curve of Fig. 3 and is recorded in Table 7.

A large number of observations of velocity in the wind tunnel were made with a standard pitot tube 12-in. from the wall in three positions :—in the plane of the screw, 8 ft. in front and 8 ft. behind. These observations are recorded in Table 8 and are plotted in Fig. 10 as V_1/V observed against $1/f$. On the same diagram is plotted the value of V_1/V calculated by formula 10.01 ; this is to be compared with the observed value in the plane of the disc. The agreement is fair except in the " Vortex ring state " where the large discrepancies as well as the unsteadiness of reading of V_1 indicate a turbulent region extending to the walls of the tunnel.

11. *Conclusions.*—It is suggested that the corrected curve of Fig. 3 employed by the methods of § 3 (1) (or if preferred of § 4) should give a good approximation to the performance of any airscrew of low pitch, and that it forms the best basis at present available for the calculation of the performance of any airscrew under any working condition, since it agrees with the Vortex theory over the range where that theory applies.

It may be noticed that the conclusion of R. & M. 885 that the resistance of an airscrew rotating at zero torque cannot exceed the resistance of an impervious disc has been somewhat modified. It is true that an airscrew at zero torque must be in the windmill brake state, so that there is still an upper limit to the resistance coefficient $\frac{T}{\pi\rho R^2 V^2} = 2f$. This upper limit, according to Figs. 2 and 3, is

$$\frac{T}{\pi\rho R^2 V^2} = \frac{2}{1 \cdot 85} = 1 \cdot 08$$

for a 3-foot screw in a 7-foot tunnel,

$$\text{and} = \frac{2}{2 \cdot 52} = \cdot 80$$

for free air, according to the method of correction of section 10, while the value for an impervious disc in free air is $0 \cdot 6$. It is suggested that the increased value of the resistance coefficient for a screw is due to the centrifugal effect causing the disturbance to spread over a larger area.

In conclusion the authors wish to record their appreciation of the assistance of Mr. Kirkup in the experimental work and of Miss Yeatman in the calculations of airscrew performance.

APPENDIX.

On the effect of rotational interference flow.—In all working states of an airscrew except the Vortex ring state, it appears probable that fluid which has once passed through the screw does not return to it, and since vorticity follows the stream and can only be formed in passing through the screw, it cannot return to the screw, so that there is zero rotation in the inflow. The title of "vortex ring state" on the other hand implies the existence of a vortex ring consisting of an isolated mass of fluid which

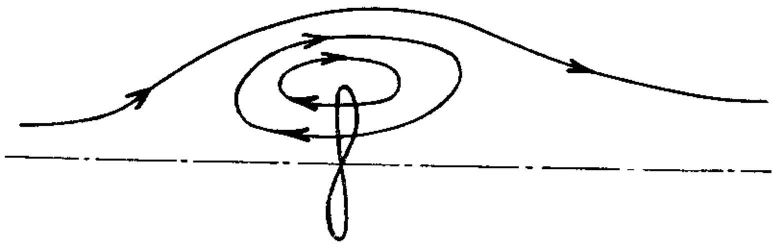

FIG. 12.

continually circulates through the screw (Fig. 12); this appears to be the only steady continuous type of motion consistent with a flow through the airscrew disc against the general stream. But the existence of a finite torque implies a continual generation of angular momentum about the axis of the screw, and for a finite mass of fluid this would imply an indefinite increase of angular momentum, apart from the small effect of viscosity at the boundary between the vortex ring and the rest of the fluid.

The only alternative seems to be to assume a state of turbulence in the region outside the airscrew in the sense of a continual mixing of fluid in the different stream lines (Fig. 13). Thus the particles of fluid

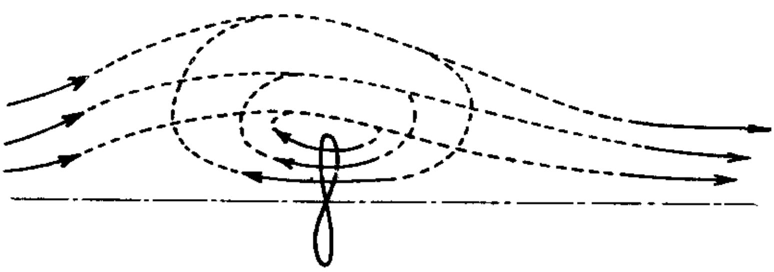

FIG. 13.

originally enclosed in a certain radius of the inflow will all pass outside the airscrew tips, but a certain (small ?) proportion only (say, $\frac{1}{4}$) of the particles are deflected to pass upstream through the airscrew disc, the remainder passing downstream. The particles which have passed upstream are deflected outwards and mix with the original stream and again the same proportion is deflected to pass through the airscrew disc. Thus only 1/16 of the fluid (say) passes through the airscrew twice, 1/64 three times, and so on; it is therefore possible for the rotation in the inflow to remain at a small finite value. The whole effect is really exactly analogous to the increase of viscosity by turbulence in other fluid problems, the normal viscosity due to the mixing of molecules on the kinetic theory being increased by the mixing of finite portions of fluid. Also it appears that the term Vortex ring state is a misnomer but may still be used for convenience as implying nothing beyond the definition of § 4(1).

If this is the true type of flow, then the order of magnitude of the rotational interference is correctly given by the assumption of zero rotation in the inflow, and the following arguments for the neglect of rotational interference apply throughout all working ranges.

In the Vortex theory the profile drag of the blades is included throughout. It appears that below the stall, the effect of profile drag on the rotational interference given by the formulæ

$$\frac{1}{1-a'} = 1 + \frac{\mu_2}{S \tan \phi}$$

$$\mu_2 = \frac{k_L \sin \phi + k_D \cos \phi}{\cos^2 \phi}$$

is very small except for very small values of ϕ and that it would be quite sufficient for practical purposes to insert the profile drag in the formula for torque only.

The question becomes important in the neighbourhood of the critical condition where u and therefore ϕ vanish. It appears from the above formulæ that $1-a'$ tends to zero, and the rotational speed tends to become large for finite values of v, T and ϕ, unless k_D is assumed to be zero. The physical interpretation of this fact is that in this critical case where the lift is normal to the airscrew disc, the profile drag produces a torque and, therefore, an angular motion in the fluid, which according to the theory could not be carried away since the axial velocity is zero. In practice a screw in this condition must resemble a centrifugal fan, the velocity at the disc being radial so that the "wake" of the blades containing the angular momentum produced by the profile drag is at first carried radially outwards, and is only carried backwards at points outside the airscrew tips. This possibility is not contemplated by the theory which requires that the radial component velocity should be small compared with the axial component. Since the difficulty of infinite rotation behind the airscrew does not appear in practice, it seems likely that the best approximation to the critical case will be obtained by neglecting the profile drag throughout in calculating the rotational interference factor a'. If this is done it appears that a' is of the order of magnitude of k_L/S; an extreme value for this corresponds to $k_L = 0\cdot 6$, $S = 20$, giving $a' = 0\cdot 03$. Accordingly in the calculations of the present report it was decided to neglect the rotational interference factor a' altogether. On the other hand, for any calculation which does not involve the Vortex ring state, the rotational interference factor may be retained, since it is theoretically accurate.

TABLE 1.

Brass Aerofoil 2·5 in. Chord.

Aerofoil data reduced to infinite aspect ratio.

k_L	Wind Speed 40 ft./sec. α (degrees).				Wind Speed 40 ft./sec. k_D				60 ft./sec. k_L	60 ft./sec. α (degrees).	60 ft./sec. k_D	70 ft./sec. α (degrees).	70 ft./sec. k_D
−0·46	146·3, 156·9, 164·9, 168·9				0·324, 0·199, 0·125, 0·081,				−0·26	−9·11	0·0645	−8·56	0·0597
−0·42	139·1		172·7		0·380		0·039		−0·20	−5·70	0·0378	−5·83	0·0374
−0·36	333·7	130·7	174·3	317·7	0·208	0·444	0·026	0·358	−0·10	−3·85	0·0219	−3·85	0·0207
−0·32	339·0	124·2	175·1	309·2	0·156	0·502	0·022	0·428	0·0	−1·90	0·0131	−2·10	0·0124
−0·26	348·1	116·4	176·2	298·0	0·080	0·563	0·017	0·516	+0·06	−0·92	0·0101	−1·12	0·0097
−0·20	353·9	109·4	177·3	288·7	0·039	0·604	0·014	0·569	0·12	+0·14	0·0077	−0·30	0·0079
−0·10	356·1	99·9	179·4	277·0	0·219	0·644	0·014	0·614	0·20	1·03	0·0061	+0·93	0·0062
0·0	358·1	90·3	181·1	268·0	0·0131	0·661	0·015	0·619	0·24	1·70	0·0059	1·70	0·0060
+0·06	359·4	84·6	182·2	263·2	0·0102	0·657	0·018	0·609	0·30	2·90	0·0060	2·92	0·0067
0·12	0·4	79·1	183·2	258·6	0·0085	0·640	0·020	0·594	0·32	3·38	0·0066	3·33	0·0069
0·20	1·36	70·8	184·7	248·6	0·0074	0·599	0·032	0·550	0·36	4·30	0·0074	4·15	0·0077
0·24	1·97	66·2	185·5	237·2	0·0073	0·574	0·040	0·471	0·40	5·16	0·0080	4·96	0·0085
0·30	3·13	58·8	187·7	226·3	0·0082	0·529	0·060	0·393	0·44	5·98	0·0086	5·78	0·0089
0·32	3·55	56·3	191·7	223·0	0·0085	0·508	0·092	0·370	0·46	6·48	0·0095	6·24	0·0095
0·36	4·45	50·3	208·3	214·9	0·0086	0·451	0·241	0·306	0·48	7·08	0·0115	6·80	0·0108
0·40	5·31	43·3			0·0102	0·397			0·50	7·92	0·0156	7·45	0·0131
0·44	6·19	21·3, 37·8			0·0109	0·178, 0·362			0·52	17·17	0·155	8·45	0·0211
0·46	6·67	17·1, 27·1, 33·7			0·012	0·141, 0·245, 0·333,			0·56	18·76	0·190	15·17	0·1363
0·48	7·25	14·6			0·013	0·116			0·60	19·74	0·219	15·94	0·1642
0·50	7·95	12·5			0·016	0·088			0·62	20·18	0·234	16·30	0·1761
0·52	9·81				0·042				0·66			17·20	0·2007
									0·70			18·22	0·2318
									0·72			18·86	0·2493

TABLE 2.

Brass Aerofoil 2·5 in. Chord.

Smoothed aerofoil data reduced to infinite aspect ratio as used in calculations.

α Degrees.	k_L	k_D	α Degrees.	k_L	k_D
−8	−0·250	0·0550	4	0·354	0·0070
−6	−0·204	0·0384	5	0·403	0·0081
−5	−0·160	0·0303	6	0·448	0·0099
−4	−0·100	0·0224	7	0·486	0·0124
−3	−0·028	0·0159	8	0·512	0·0168
−2	+0·032	0·0106	10	0·526	0·0450
−1	0·089	0·0079	12	0·508	0·078
0	0·147	$0{\cdot}0063_5$	14	0·486	0·115
1	0·202	0·0057	16	0·468	0·147
2	0·254	0·0056	20	0·443	0·204
3	0·304	0·0060			

TABLE 3.

Performance data of two-bladed airscrew of aerofoils.

Blade angle (measured from undersurface) 0°.

V = velocity uncorrected for tunnel interference.

V/nD	n	k_T	k_Q	V/nD	n	k_T	k_Q	V/nD	n	k_T	k_Q
0·0	24·9	0·0042	0·00090	−0·108	21·8	0·0154	{0·00097 0·00086	−0·574	16·0	0·1230	−0·00343
0·0	22·6	0·0041	0·00091	−0·114	14·7	0·0169	0·00078	−0·678	13·5	0·1428	−0·00327
0·072	23·2	0·0010	0·00094	−0·127	18·6	0·0181	0·00103	−0·711	12·9	0·1481	−0·00310
0·082	20·4	0·0	0·00093	−0·155	21·6	0·0236	0·00071	−0·754	14·0	0·1589	−0·00311
0·099	23·9	−0·0009	0·00096	−0·156	15·15	0·0228	0·00073	−0·879	12·0	0·1802	−0·00252
0·105	15·9	−0·0013	0·00093	−0·174	19·3	0·0266	0·00087	−1·068	9·9	0·2121	−0·00202
0·111	21·3	−0·0023	0·00100	−0·215	22·0	0·0367	0·00054				
0·139	24·2	−0·0053	0·00100	−0·298	15·9	0·0602	−0·00027	−0·510	18·0	0·1134	−0·00305
0·144	16·4	−0·0058	0·00103	−0·319	10·5	0·0665	+0·00024	−0·557	16·5	0·1249	−0·00343
0·153	21·9	−0·0076	0·00100	−0·321	18·0	0·0660	−0·00052	−0·561	13·3	0·1291	−0·00324
0·175	19·2	−0·0106	0·00104	−0·346	16·7	0·0727	−0·00104	−0·584	12·8	0·1276	−0·00345
				−0·366	15·8	0·0772	−0·00133	−0·592	15·5	0·1305	−0·00366
0·0	21·2	0·0046	0·00072	−0·399	18·7	0·0880	−0·00144	−0·681	11·0	0·1469	−0·00293
0·0	23·6	0·0047	0·00105	−0·401	11·8	0·0902	−0·00101	−1·686	7·7	0·3538	−0·00106
−0·069	24·2	0·0107	0·00091	−0·411	14·1	0·0894	−0·00167	−1·918	6·8	0·400	−0·00087
−0·074	22·5	0·0114	0·00080	−0·446	16·8	0·1000	−0·00223	−2·31	5·6	0·4965	−0·00031
−0·091	18·3	0·0140	0·00071	−0·486	15·4	0·108	−0·00266				
−0·096	24·7	0·0137	0·00086								

Table 3—*continued.*

Performance data of two-bladed airscrew of aerofoils.

Blade angle (measured from undersurface) — 4°.

V = velocity uncorrected for tunnel interference.

V/nD	n	k_T	k_Q	V/nD	n	k_T	k_Q	V/nD	n	k_T	k_Q
0·073	23·0	−0·0069	0·00113	0	22·6	−0·0014	0·00107	−0·096	24·6	0·0030	0·00088
0·084	20·0	−0·0086	0·00119	0	17·8	−0·0017	0·00107	−0·097	24·4	0·0031	0·00089
0·095	24·9	−0·0096	0·00115	−0·068	24·8	+0·0010	0·00095	−0·129	18·2	0·0062	0·00081
0·097	17·4	−0·0106	0·00124	−0·080	20·9	0·0016	0·00095	−0·162	25·3	0·0131	0·00057
0·105	22·4	−0·0111	0·00125	−0·095	17·6	0·0029	0·00089	−0·215	19·1	0·0220	0·00038
0·139	24·1	−0·0167	0·00142	−0·148	22·6	0·0106	0·00068	−0·372	24·6	0·0603	−0·00156
0·142	16·7	−0·0175	0·00146	−0·156	21·4	0·0115	0·00063	−0·418	21·9	0·0708	−0·00225
0·160	21·2	−0·0207	0·00154	−0·191	17·6	0·0173	0·00046	−0·470	19·5	0·0826	−0·00298
0·194	24·3	−0·0293	0·00179	−0·243	23·9	0·0293	0·00014	−0·528	17·4	0·0955	−0·00375
0·199	16·8	−0·0302	0·00180	−0·310	18·7	0·0403	−0·00109	−0·589	15·6	0·1081	−0·00464
0·222	21·3	−0·0365	0·00195	−0·329	22·7	0·0506	−0·00102	−0·661	13·9	0·1223	−0·00532
0·259	18·2	−0·0465	0·00222	−0·381	19·6	0·0609	−0·00173	−0·744	12·3	0·1378	−0·00570
0·265	24·3	−0·0480	0·00225	−0·418	21·9	0·0707	−0·00224	−0·838	10·9	0·1528	−0·00593
0·307	24·3	−0·0587	0·00250	−0·473	15·8	0·0835	−0·00297	−0·954	9·6	0·1695	−0·00542
0·340	19·1	−0·0672	0·00272	−0·475	19·3	0·0844	−0·00307	−1·145	8·0	0·2040	−0·00550
0·393	16·4	−0·0828	0·00309	−0·518	11·2	0·0922	−0·00371	−1·493	6·1	0·2770	−0·00625
0·395	18·9	−0·0819	0·00304	−0·529	17·3	0·0960	−0·00392				
0·449	16·6	−0·0962	0·00332	−0·598	15·3	0·1110	−0·00492				

TABLE 3—*continued.*

Performance data of two-bladed airscrew o_j aerofoils.

Blade angle (measured from undersurface) $+ 4°$.

V = velocity uncorrected for tunnel interference.

V/nD	n	k_T	k_Q	V/nD	n	k_T	k_Q	V/nD	n	k_T	k_Q	V/nD	n	k_T	k_Q
0	25·2	0·0247	0·00126	0·343	16·9	−0·0220	0·00072	−0·374	15·5	0·0982	−0·00001	0	23·8	0·0249	—
0	26·9	0·0253	0·00126	0·360	16·1	−0·0263	0·00060	−0·473	12·3	0·1215	−0·00068	0	21·9	0·0245	—
0·067	25·0	0·0226	0·00121	−0·067	24·8	+0·0254	0·00126	−0·757	7·7	0·1778	+0·00192	−0·380	19·7	—	0
0·070	24·0	0·0226	0·00122	−0·086	19·3	0·0279	0·00131	−0·426	21·5	0·1133	−0·00069	−0·381	17·6	—	0
0·074	22·5	0·0205	0·00121	−0·146	19·8	0·0398	0·00125	−0·519	17·7	0·1339	−0·00175	−0·388	15·0	—	0
0·084	19·8	0·0199	0·00122	−0·155	10·8	0·0449	0·00125	−0·760	12·1	0·1797	+0·00175	−0·394	13·5	—	0
0·093	25·4	0·0203	0·00122	−0·207	13·9	0·0538	0·00118	−1·038	12·6	0·2340	0·00338	−0·393	12·0	—	0
0·099	16·9	0·0183	0·00119	−0·380	12·5	0·1010	0	−1·416	9·2	0·3117	0·00506	−0·420 ?	9·9	—	0
0·100	23·7	0·0186	0·00122	−0·551	8·6	0·1417	0·00021	−1·766	5·2	0·3885	0·00666				
0·126	18·8	0·0148	0·00118	−0·825	5·7	0·1588	0·00242	−0·424	21·6	0·1070	−0·00069				
0·128	26·2	0·0152	0·00118	−0·073	23·0	0·0277	0·00127	−0·445	20·6	0·1175	−0·00080				
0·140	24·0	0·0136	0·00116	−0·077	21·7	0·0277	0·00129	−0·466	19·7	0·1220	−0·00096				
0·156	21·5	0·0113	0·00114	−0·116	24·9	0·0337	0·00126	−0·496	18·5	0·1300	−0·00104				
0·181	18·5	0·0076	0·00109	−0·188	25·2	0·0479	0·00108	−0·509	18·0	0·1292	−0·00104				
0·223	15·0	0	0·00099	−0·215	22·0	0·0540	0·00099	−0·548	16·7	0·1401	−0·00073				
0·231	25·1	0	0·00101	−0·244	23·8	0·0600	0·00092	−0·585	15·7	0·1489	−0·00043				
0·296	19·6	−0·0136	0·00080	−0·291	19·9	0·0724	0·00067	−0·624	14·7	0·1573	+0·00028				
0·307	18·9	−0·0146	0·00087					−0·647	14·2	0·1564	0·00046				

TABLE 3—*continued.*

Performance data of two-bladed airscrew of aerofoils.

Blade angle (measured from undersurface) — 2·6°.

V = velocity uncorrected for tunnel interference.

V/nD	n	k_T	k_Q	V/nD	n	k_T	k_Q
0	24·4	0	0·00095	0	24·2	0·0	0·00095
0·068	24·6	−0·0041	0·00105	−0·069	24·4	0·0044	0·00085
0·084	19·9	−0·0058	0·00111	−0·088	24·7	0·0063	0·00083
0·095	24·8	−0·0067	0·00113	−0·090	18·6	0·0063	0·00084
0·109	21·6	−0·0082	0·00118	−0·103	16·3	0·0071	0·00083
0·110	15·3	−0·0091	0·00137	−0·122	19·4	0·0094	0·00077
0·129	18·3	−0·0116	0·00126	−0·133	25·1	0·0128	0·00069
0·139	24·1	−0·0149	0·00131	−0·144	16·3	0·0116	0·00072
0·163	20·5	−0·0195	0·00139	−0·172	19·5	0·0171	0·00055
0·177	18·9	−0·0221	0·00145	−0·190	24·8	0·0221	0·00044
0·196	24·1	−0·0256	0·00150	−0·205	16·4	0·0227	0·00041
0·233	20·2	−0·0346	0·00166	−0·225	21·0	0·0303	−0·00018
0·268	24·1	−0·0420	0·00190	−0·250	25·8	0·0357	−0·00029
0·280	16·8	−0·0468	0·00191	−0·270	17·4	0·0421	+0·00014
0·344	18·8	−0·0615	0·00212	−0·298	21·6	0·0450	−0·00080
0·382	24·0	−0·0715	0·00226	−0·333	27·5	0·0563	−0·00127
0·438	14·7	−0·0844	0·00248	−0·348	18·5	0·0569	−0·00209
0·475	19·3	−0·0935	0·00260	−0·385	23·8	0·0685	−0·00183
				−0·430	21·3	0·0804	−0·00254
				−0·538	17·12	0·104	−0·00381

Table 4.

Performance of four-bladed airscrew No. 1. P/D 0·3.

V = velocity uncorrected for tunnel interference.

V/nD	n	k_T	k_Q	V/nD	n	k_T	k_Q
0·286	18·7	0·0445	0·00480	−0·191	19·8	0·0866	0·00532
0·275	19·5	0·0477	0·00487	−0·215	22·3	0·0890	0·00523
0·264	20·3	0·0504	0·00491	−0·235	20·3	0·0950	0·00549
0·255	21·0	0·0533	0·00499	−0·271	17·7	0·1090	0·00578
0·241	22·3	0·0578	0·00512	−0·287	18·7	0·1120	0·00572
0·226	23·7	0·0605	0·00516	−0·310	19·4	0·1170	0·00547
0·216	24·8	0·0633	0·00522	−0·340	14·1	0·132	0·00555
0·200	20·7	0·0665	0·00537	−0·359	14·9	0·140	0·00520
0·188	22·1	0·0694	0·00543	−0·391	15·0	0·150	0·00503
0·169	24·6	0·0735	0·00543	−0·453	14·5	0·174	0·00438
0·161	25·7	0·0747	0·00543	−0·544	12·2	0·214	0·00350
0	17·9	0·0978	0·00642	−0·665	10·0	0·292	0·00176
0	17·2	0·0883	0·00583	−0·726	9·1	0·318	0·00162
−0·070	17·0	0·0903	0·00585				0·00284
−0·075	21·5	0·0903	0·00553	−0·843	11·1	0·364	0·00456
−0·084	20·3	0·0887	0·00497	−0·885	7·5	0·378	0·00723
−0·110	15·5	0·0872	0·00506	−0·930	10·0	0·367	0 to 0·0124
−0·123	19·4	0·0887	0·00494	−1·03	9·1	0·448	0 to 0·0157
−0·134	17·9	0·0819	0·00490	−1·15	8·1	0·558	0 to 0·0188
−0·145	20·2	0·0836	0·00491	−1·324	7·1	0·581	0·0194
−0·162	18·1	0·0798	0·00528	−1·710	5·5	0·707	0·0236

TABLE 5.

Observed and calculated performance data of two-bladed airscrew of aerofoils.

Blade angle (measured from undersurface) = 4°.

V = velocity uncorrected for tunnel interference.

V/nD	Observed (smoothed)		Calculated	
	k_T	k_Q	k_T	k_Q
−1·8	0·391	0·00678	—	—
−1·6	0·350	0·00592	—	—
−1·4	0·308	0·00504	—	—
−1·2	0·267	0·00406	—	—
−1·0	0·226	0·00323	—	—
−0·9	0·205	0·00271	—	—
−0·8	0·185	0·00208	—	—
−0·7	0·168	0·00121	—	—
−0·613	0·154	zero	—	—
−0·6	0·152	−0·00020	—	+0·00237
−0·5	0·131	−0·00102	0·1198	−0·00002
−0·4	0·105	−0·00049	0·0985	−0·00005
− ·36	0·093	zero	—	—
−0·3	0·076	+0·00058	0·0764	+0·00078
−0·2	0·051	0·00110	0·0516	0·00131
−0·1	0·030	0·00127	0·0308	0·00141
−0·05	0·025	—	—	—
0	0·025	0·00127	0·0243	0·00143
+0·05	0·024	—	—	—
0·1	0·019	0·00121	0·0191	0·00133
0·2	0·005	0·00107	0·0050	0·00118
0·3	−0·013	0·00085	−0·0127	0·00093
0·4	−0·034	0·00050	−0·0344	0·00060
0·5	—	—	−0·0595	0·00021

TABLE 5—*continued.*

Observed and calculated performance data of two-bladed airscrew of aerofoils.

Blade angle (measured from undersurface) = 0°.

V = velocity uncorrected for tunnel interference.

V/nD	Observed (smooth d)		Calculated	
	k_T	k_Q	k_T	k_Q
−2·2	0·467	−0·00049	—	—
−2·0	0·421	−0·00070	—	—
−1·8	0·376	−0·00092	—	—
−1·6	0·330	−0·00116	—	—
−1·4	0·284	−0·00144	—	—
−1·2	0·240	−0·00177	—	—
−1·0	0·202	−0·00219	—	—
−0·9	0·185	−0·00243	—	—
−0·8	0·167	−0·00286	—	—
−0·7	0·150	−0·00335	—	−0·00083
−0·6	0·131	−0·00363	0·1142	−0·00287
−0·5	0·110	−0·00291	0·1015	−0·00258
−0·4	0·088	−0·00154	0·0821	−0·00139
−0·3	0·061	−0·00028	0·0573	−0·00012
−0·275	0·054	zero	—	—
−0·2	0·033	+0·00067	0·0326	+0·00055
−0·1	0·014	0·00100	0·0140	0·00088
0	$0·005_5$	0·00091	0·0035	0·00102
+0·1	$-0·001_5$	0·00095	−0·0033	0·00118
0·2	−0·014	0·00110	−0·0159	0·00121
0·3	—	—	—	0·00131
0·4	—	—	—	—
0·5	—	—	—	—

TABLE 5—*continued.*

Observed and calculated performance data of two-bladed airscrew of aerofoils.

Blade angle (measured from undersurface) = − 2·6°.

V = velocity uncorrected for tunnel interference.

V/nD	Observed (smoothed)		Calculated	
	k_T	k_Q	k_T	k_Q
−0·8	—	—	0·1306	—
−0·7	—	—	0·1247	−0·00500
−0·6	—	—	0·1124	−0·00481
−0·5	0·096	−0·00340	0·0938	−0·00345
−0·4	0·072	−0·00210	0·0722	−0·00189
−0·3	0·047	−0·00075	0·0463	−0·00052
−0·245	0·033	zero	—	—
−0·2	0·023	+0·00045	0·0225	+0·00035
−0·1	0·007	0·00081	0·0071	0·00092
0	0	0·00095	−0·0006	0·00113
+0·1	−0·0075	0·00117	−0·0073	0·00130
0·2	−0·0265	0·00154	−0·0242	0·00161
0·3	−0·051	0·00197	−0·0447	0·00206
0·4	−0·076	0·00233	—	—
0·5	−0·098	0·00268	—	—

Blade angle (measured from undersurface) = − 4°.

V/nD	Observed (smoothed)		Calculated	
	k_T	k_Q	k_T	k_Q
−1·4	0·256	−0·00600	—	—
−1·2	0·215	−0·00558	—	—
−1·0	0·178	−0·00548	—	—
−0·9	0·162	−0·00570	—	—
−0·8	0·146	−0·00578	—	−0·00530
−0·7	0·130	−0·00555	0·1231	−0·00608
−0·6	0·111	−0·00478	0·1077	−0·00548
−0·5	0·090	−0·00342	0·0869	−0·00369
−0·4	0·065	−0·00200	0·0654	−0·00201
−0·3	0·041	−0·00067	0·0399	−0·00047
−0·24	0·027$_5$	zero	—	—
−0·2	0·019	+0·00037	0·0198	+0·00036
−0·1	0·003	0·00091	0·0050	0·00091
0	−0·001$_5$	0·00106	0	0·00114
+0·1	−0·010$_5$	0·00127	−0·0109	0·00135
0·2	−0·031	0·00180	−0·0294	0·00201
0·3	−0·057	0·00249	−0·0515	0·00272
0·4	−0·084	0·00310	—	—
0·5	−0·110	0·00355	—	—

TABLE 5—*continued.*

Observed and calculated performance data of four-bladed airscrew No. 1. $P/D = 0 \cdot 3$.

V = velocity uncorrected for tunnel interference.

V/nD	Observed (smoothed)		Calculated	
	k_T	k_Q	k_T	k_Q
$-1 \cdot 3$	0·575	0·0188	—	—
$-1 \cdot 2$	0·562	0·0167	—	—
$-1 \cdot 1$	0·502	unsteady	—	—
$-1 \cdot 0$	0·431	,,	—	—
$-0 \cdot 9$	0·385	0·0080	—	—
$-0 \cdot 8$	0·346	0·0032	—	—
$-0 \cdot 7$	0·307	0·0015	—	—
$-0 \cdot 6$	0·255	0·0026	0·239	0·00188
$-0 \cdot 5$	0·196	0·0040	0·209	0·00399
$-0 \cdot 4$	0·153	0·0050	0·168	0·00549
$-0 \cdot 3$	0·118	0·0057	0·132	0·00611
$-0 \cdot 2$	0·086	0·0053	0·104	0·00611
$-0 \cdot 1$	0·090	0·0050	0·087	0·00577
0	0·093	0·0056	0·078	0·00562
$+0 \cdot 1$	0·085	0·0056	0·074	0·00553
$0 \cdot 2$	0·067	0·0053	0·066	0·00521
$0 \cdot 3$	0·042	0·0048	0·044	0·00468

TABLE 5 (*a*).

Observed and calculated values of k_T at zero torque.

Airscrew of Aerofoils.

Blade Angle.	V/nD observed.	k_T Observed.		k_T Calculated.	
		Screw Mounted on Motor Shaft.	Screw Mounted on Ball Bearings.	$\frac{V}{nD}$	k_T
4°	$-0 \cdot 613$	0·154	—	$-0 \cdot 50$	0·120
	$-0 \cdot 36$	0·093	—	$-0 \cdot 392$	0·097
1°	$-0 \cdot 306$	—	0·065	$-0 \cdot 310$	0·065
0°	$-0 \cdot 275$	0·054	—	$-0 \cdot 290$	0·055
0°	$-0 \cdot 289$	—	0·055		
$-0 \cdot 5°$	$-0 \cdot 283$	—	0·052	$-0 \cdot 28$	0·050
$-1°$	$-0 \cdot 283$	—	0·049	$-0 \cdot 27$	0·046
$-2°$	$-0 \cdot 271$	—	0·040	$-0 \cdot 256$	0·037
$-2 \cdot 6°$	$-0 \cdot 245$	0·033	—	$-0 \cdot 24$	0·032
$-3°$	$-0 \cdot 269$	—	0·036	$-0 \cdot 25$	0·032
$-4°$	$-0 \cdot 24$	$0 \cdot 027_5$	—	$-0 \cdot 255$	0·030
$-6°$	$-0 \cdot 287$	—	0·026	—	—

TABLE 6.

Specimen of calculations for airscrew of aerofoils, blade angle = 4°.

1	2	3	4	5	6	7	8	9
Independent of x						$x = 0 \cdot 75$		
α	φ	k_L	k_D	μ_1	μ_2*	u/nD†	$\frac{dk_T}{dx}$	$\frac{dk_Q}{dx}$*
−1	5	0·089	0·0079	0·0886	0·0158	0·2062	0·0342	0·0023
0	4	0·147	0·0063	0·1468	0·0167	0·1648	0·0567	0·0024
+2	2	0·254	0·0056	0·2540	0·0145	0·0823	0·0981	0·0021
3	1	0·304	0·0060	0·3038	0·0113	0·0413	0·1173	0·0016
4	0	0·354	0·0070	0·3540	0·0070	0	0·1367	0·0010

Analysis only.

10	11				12	13	14	15	16	17
u/nD	$\frac{dk_T}{dx}$ (Cross plotted).				k_T	Boss correction	k_T corrected	V/nD	$\frac{1}{F}$	$\frac{1}{f}$
	$x = 0 \cdot 4$	0·6	0·75	0·9						
0·20	−0·018	+0·006	0·038	0·080	0·0149	0·0003	0·0146	+0·138	4·31	2·05
0·15	−0·003	0·029	0·063	0·110	0·0317	0·0001	0·0316	−0·107	1·12	0·57
0·10	+0·012	0·050	0·089	0·140	0·0489	0·0001	0·0488	−0·191	0·34	1·175
0·05	0·026	0·070	0·114	0·169	0·0646	0	0·0646	−0·258	0·061	1·642
0	0·039	0·088	0·137	0·197	0·0794	0	0·0794	−0·314	0	1·951

* Recalculation only. † Analysis only.

Recalculation only.

18	19	20	21
α	$x = 0\cdot75$, etc.		
	$\frac{1}{F}$	$\frac{1}{f}$	V/nD
−1	2·946	0·94	+0·117
0	1·131	0·53	−0·113
+2	0·160	1·385	−0·240
3	0·033	1·68	−0·290
4	0	1·85	−0·328

22	23				24	25	26				27
V/nD	$\frac{dk_T}{dx}$ (Cross plotted)				k_T	k_T corrected	$\frac{dk_Q}{dx}$ (Cross plotted)				k_Q
	$x = 0\cdot4$	0·6	0·75	0·9			$x = 0\cdot4$	0·6	0·75	0·9	
+0·1	0·004	0·020	0·035	0·057	0·0193	0·0191	0·00026	0·0011	0·0023	0·0042	0·00133
0	0·009	0·026	0·042	0·065	0·0245	0·0243	0·00032	0·0012	0·0024	0·0043	0·00143
−0·1	0·016	0·034	0·054	0·079	0·0309	0·0308	0·00037	0·0012	0·0024	0·0042	0·00141
−0·2	0·030	0·058	0·084	0·117	0·0516	0·0516	0·0002	0·00115	0·0023	0·0039	0·00131
−0·3	0·052	0·089	0·121	0·163	0·0764	0·0764	−0·0002	0·0005	0·0014	0·0030	0·00078

TABLE 7.

Smoothed values of the variables $\frac{1}{F}$ *and* $\frac{1}{f}$ *of Figures* 2 *and* 3, *and also of* $\frac{1}{f_1}$ *and* $\frac{V_1}{V}$ *calculated from formula* 10·01.

$\frac{1}{F}$	$\frac{1}{f}$	$\frac{1}{f_1}$	$\frac{V_1}{V}$
6·0	8·00	—	1·023
5·0	6·90	—	1·025
4·0	5·80	6·03	1·028
3·0	4·87	5·23	1·036
2·0	4·07	4·48	1·050
1·5	3·68	4·14	1·061
1·0	3·28	3·79	1·075
0·75	3·06	3·60	1·085
0·5	2·80	3·37	1·097
0·25	2·48	3·08	1·115
0	1·85	2·52	1·168
0·25	1·25	1·93	1·243
0·5	0·96	1·60	1·289
0·75	0·77	1·37	1·334
1·0	0·60	0·15	1·385
1·5	0·30	0·24	—
2·0	0	—	—

For values of $\frac{1}{F} > 6 \cdot 0, \frac{1}{f} = \frac{1}{F} \pm 2.$

the plus or minus sign being taken according to the following table :—

$\frac{1}{F}$	State	
	W	N
positive - - -	+	−
negative - - -	−	+

TABLE 8.

Observed velocities (V_1/V) one foot from tunnel wall for values of $1/f$.
(For calculated values *see* Table 7.)

(*a*) Four-bladed Airscrew No. 1 $P/D = 0{\cdot}3$.

$\frac{1}{f}$	V_1/V			Working condition
	8 ft. in front of screw	In plane of screw	8 ft. in rear of screw	
6·49	0·99	1·04	1·09	W
4·73	0·99	1·07	$1{\cdot}14_5$	,,
3·06	0·98	1·16	1·21	,,
	0·99	1·05	1·09	,,
1·53	0·97	1·37	1·14	V
1·38	0·97	1·42	1·13	,,
0·81	0·99	$1{\cdot}94_5$	1·07	,,
0·32	0·98	1·61	1·09	,,
0·55	1·00	0·96	0·87	N
1·74	1·02	1·00	0·96	,,
2·89	0·98	$1{\cdot}01_5$	0·97	,,

(*b*) Airscrew of Aerofoils. Blade angle (measured from undersurface) $= 4°$.

10·10		1·04	1·05	W
7·21		1·04	1·06	,,
4·21		1·07	1·15	,,
3·89		1·07	1·15	,,
3·60		1·09	1·17	,,
3·37		1·09	1·19	,,
3·36		1·08	1·19	,,
3·15		1·09	1·20	,,
2·97		1·10	1·22	,,
2·80		1·11	—	,,
2·65		1·11	1·24	,,
2·52		1·12	—	,,
2·24		1·16	1·15	,,
			1·22	,,
1·68		1·25	1·10	,,
0·84		1·70	1·15	,,
		1·73	1·06	,,
		1·71	1·13	,,
0·63		1·98	1·13	,,
		2·04	1·15	,,
0·42		2·21	1·05	,,
			0·82	,,
0·34		1·83	1·05	,,
		1·99		,,
0·28		1·34	0·82	,,
		1·50		,,
0·44		0·91	0·79	N
0·47		0·91	0·80	,,
1·18		0·92	0·88	,,
1·69		1·00	0·90	,,
3·39		0·97	0·89	,,

TABLE 8—*continued.*

Observed velocities (V_1/V).

(c) Airscrew of Aerofoils. Blade angle (measured from undersurface) = 0°.

$\frac{1}{f}$	V_1/V		Working condition
	In plane of screw	8 ft. in rear of screw	
8·33	1·04	1·06	W
6·74	1·04	1·08	,,
5·36	1·05	1·10	,,
4·20	1·07	1·14	,,
2·98	1·10	1·19	,,
2·80	1·11	1·22	,
2·74	1·13	1·21	,,
2·60	1·11	1·22	,,
2·47	1·13	1·09	,,
2·41	1·15	1·25	,,
2·32	1·15	1·27	,,
1·98	1·19	1·22	,,
1·77	1·22	—	V
1·68	1·26	1·17	,,
1·40	1·34	1·12	,,
1·20	1·37	1·08	,,
1·20	1·47	1·13 1·25	,, ,,
1·06	1·47	1·12	,,
0·93	1·63	1·42	,,
0·93	—	1·34 1·21	,, ,,
0·76	— 1·76	1·13 1·28	,, ,,
0·70	— 1·82	1·10 1·15	,, ,,

FIG. 2.

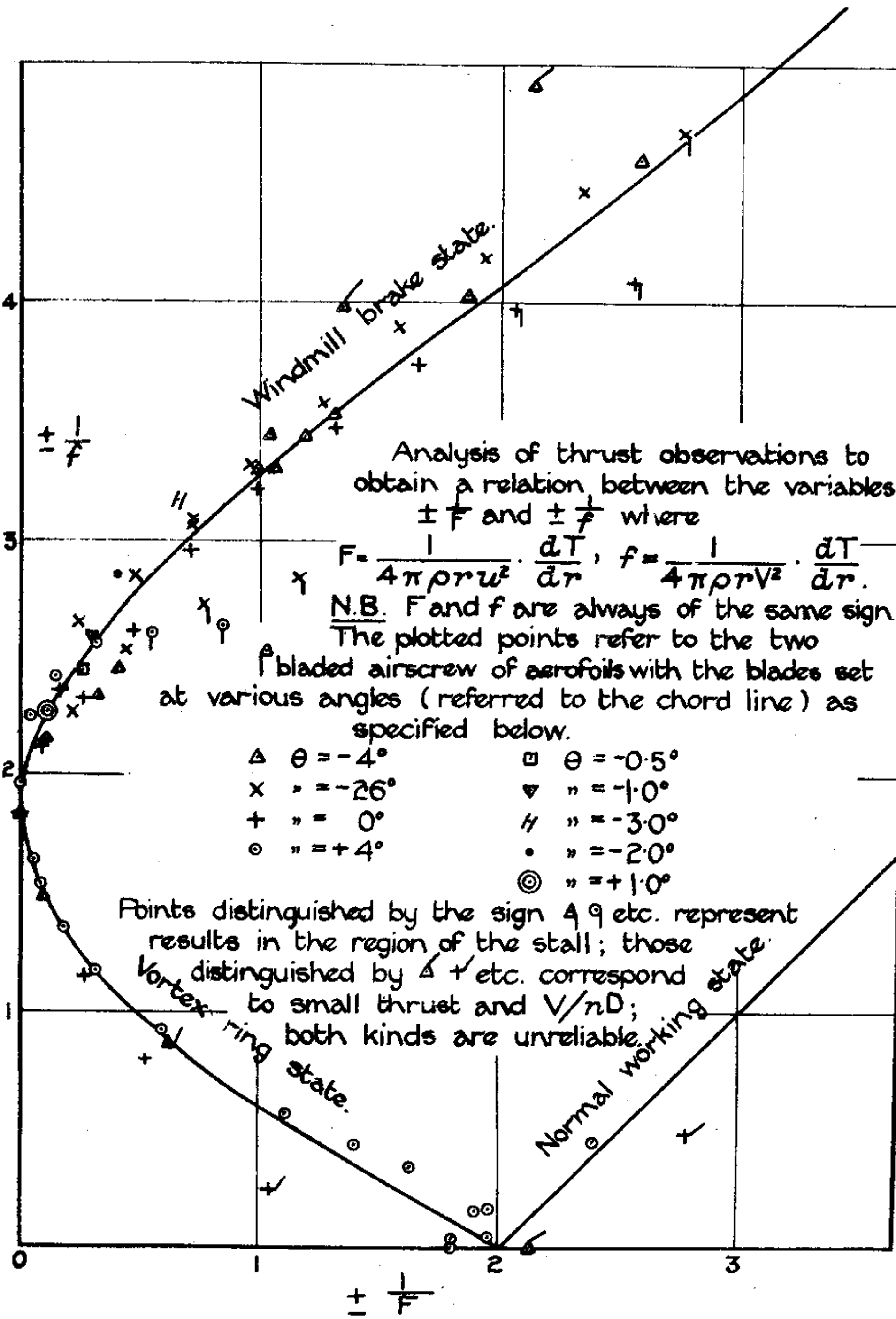

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FIG. 3.

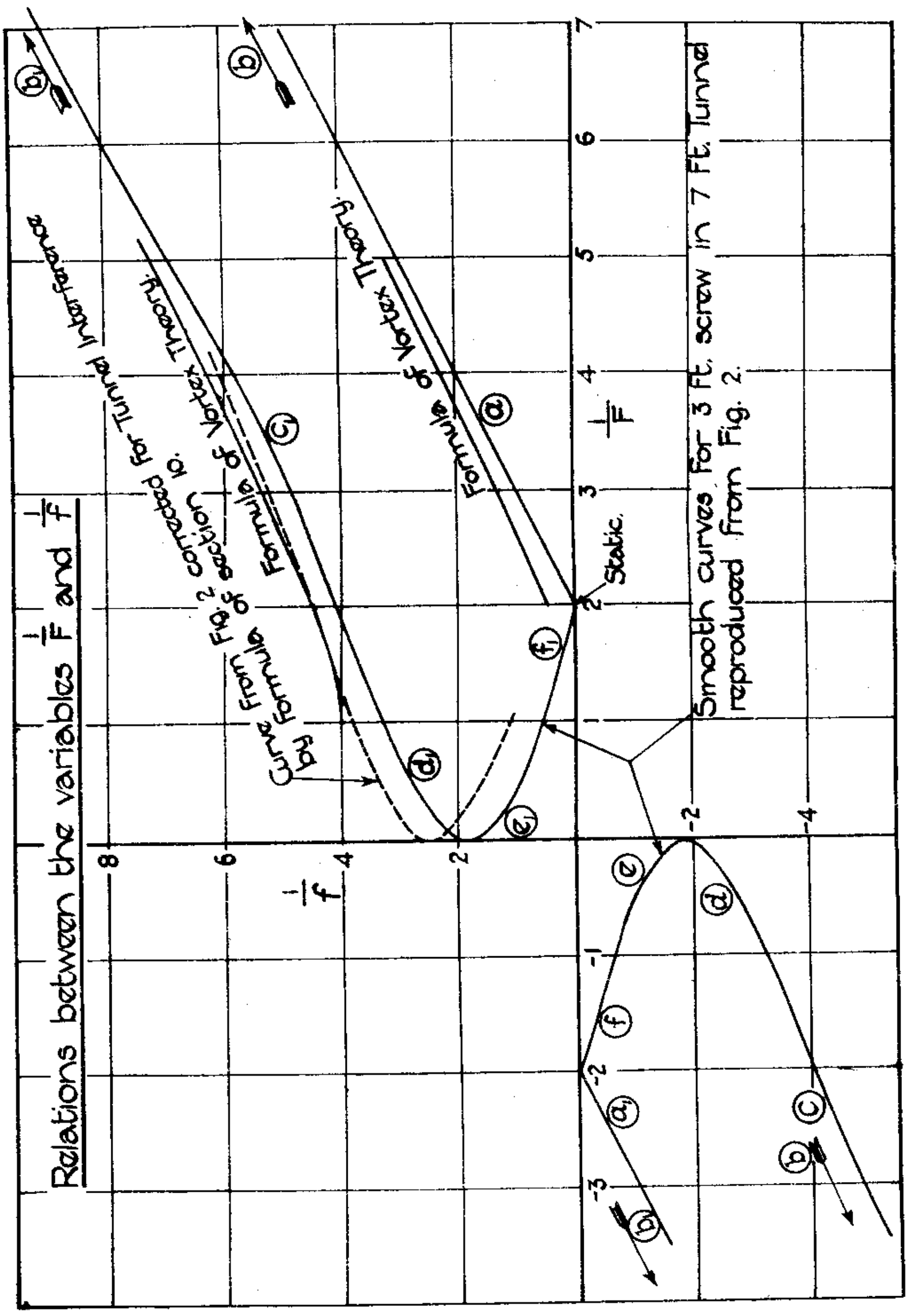

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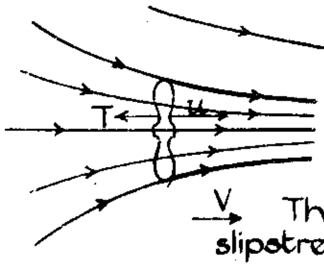
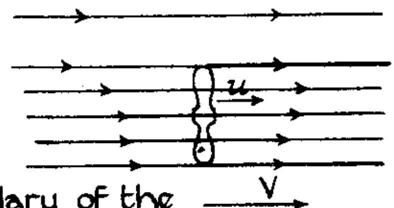
FIG. 4.

Types of Flow through an Airscrew for various working conditions.

(a) V small +ive, u +ive, T +ive.

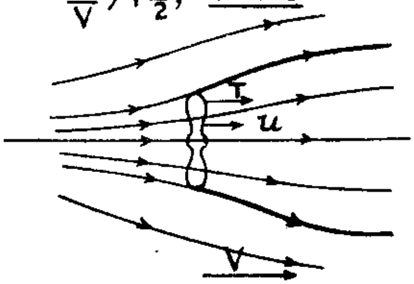


(b) V +ive, $u = V$, T zero.

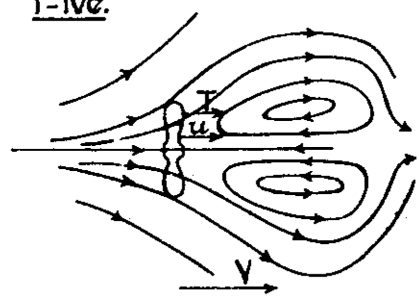


The boundary of the slipstream is shown by thickened lines.

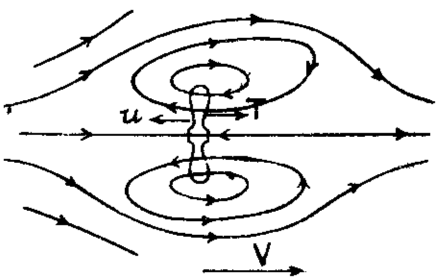
(c) u +ive, $u < V$, $\frac{u}{V} > +\frac{1}{2}$, T -ive



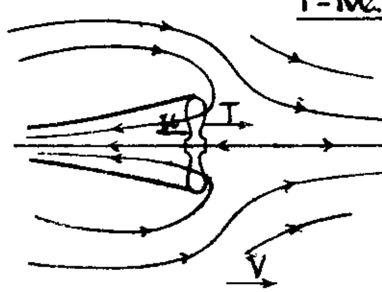
(d) u +ive. $\frac{u}{V} < +\frac{1}{2}$, T-ive.



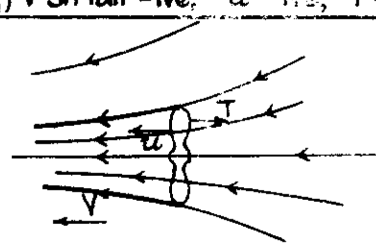
(e) u -ive, $\frac{u}{V}$ small, T-ive.



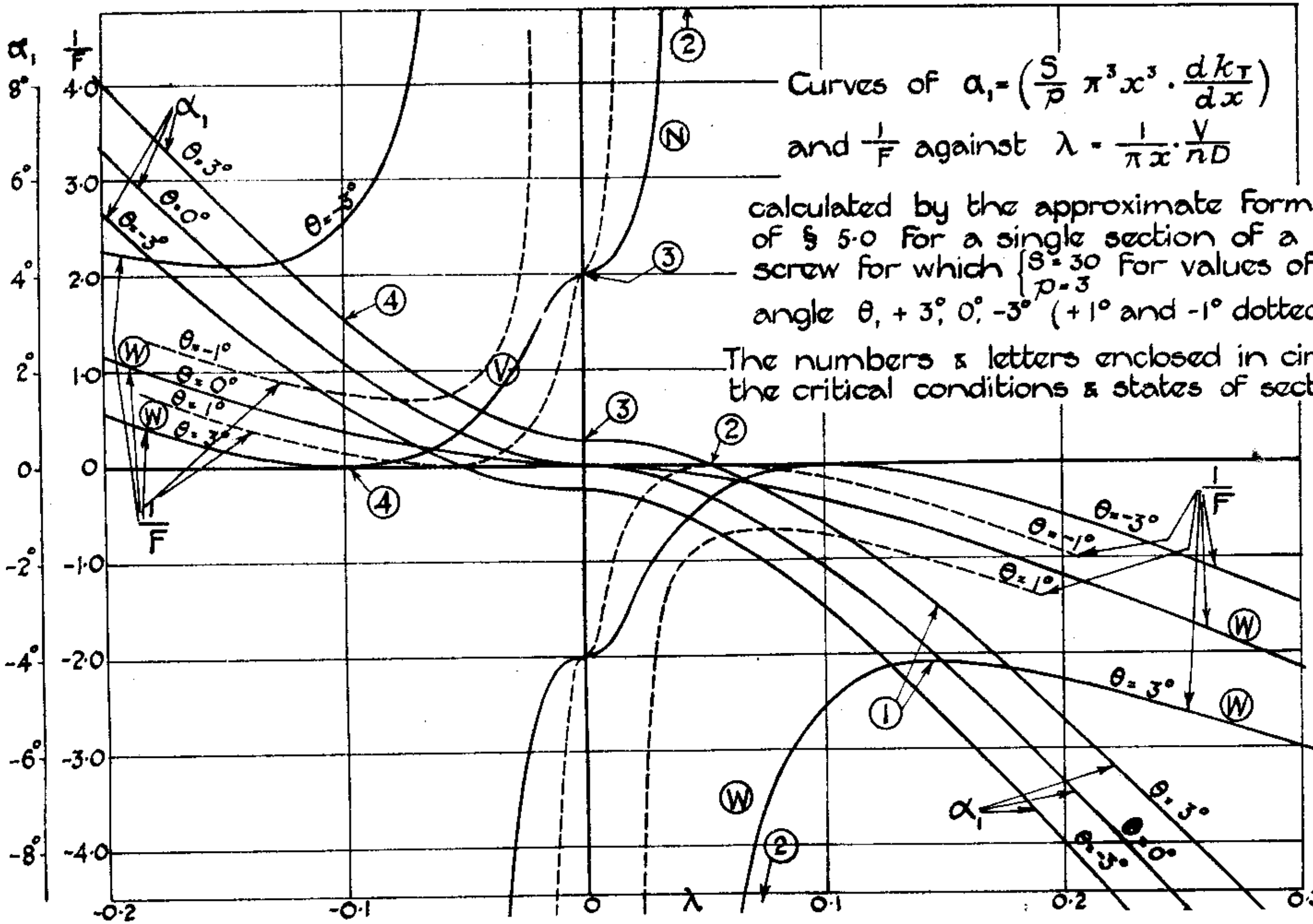
(F) u -ive, V small +ive, T-ive.



(a_1) V small -ive, u -ive, T -ive.



R.&M. 1014.



Curves of $\alpha_1 = \left(\frac{S}{p}\,\pi^3 x^3 \cdot \frac{dk_T}{dx}\right)$ and $\frac{1}{F}$ against $\lambda = \frac{1}{\pi x} \cdot \frac{V}{nD}$

calculated by the approximate formulae of § 5·0 for a single section of a low pitched screw for which $\begin{cases} S = 30 \\ p = 3 \end{cases}$ for values of blade angle θ, + 3°, 0°, -3° (+ 1° and -1° dotted curves).

The numbers & letters enclosed in circles mark the critical conditions & states of section 5·1

FIG. 5.

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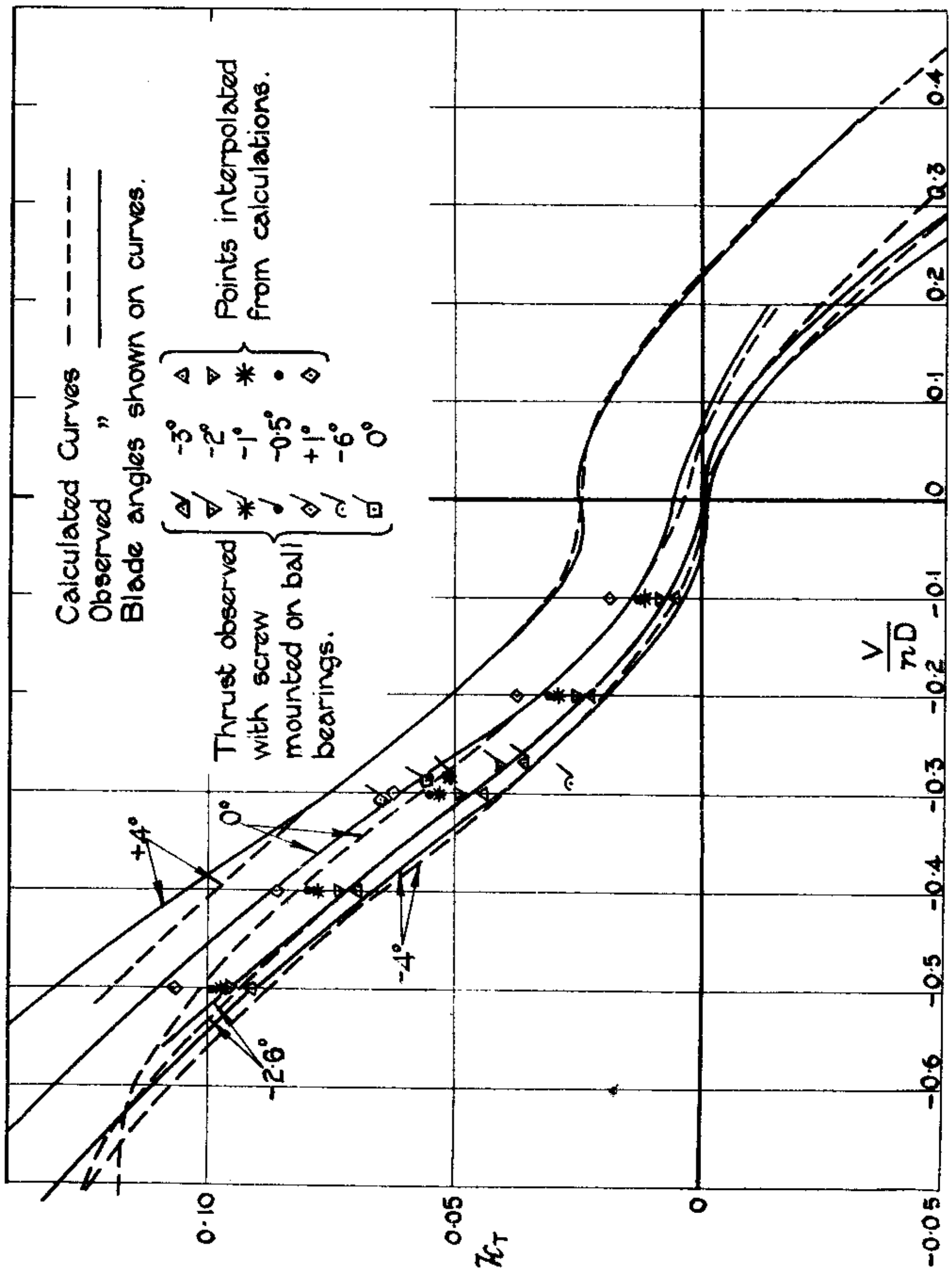
R.&M.1014.

Fig.6.

Airscrew of Aerofoils. Thrust Curves.



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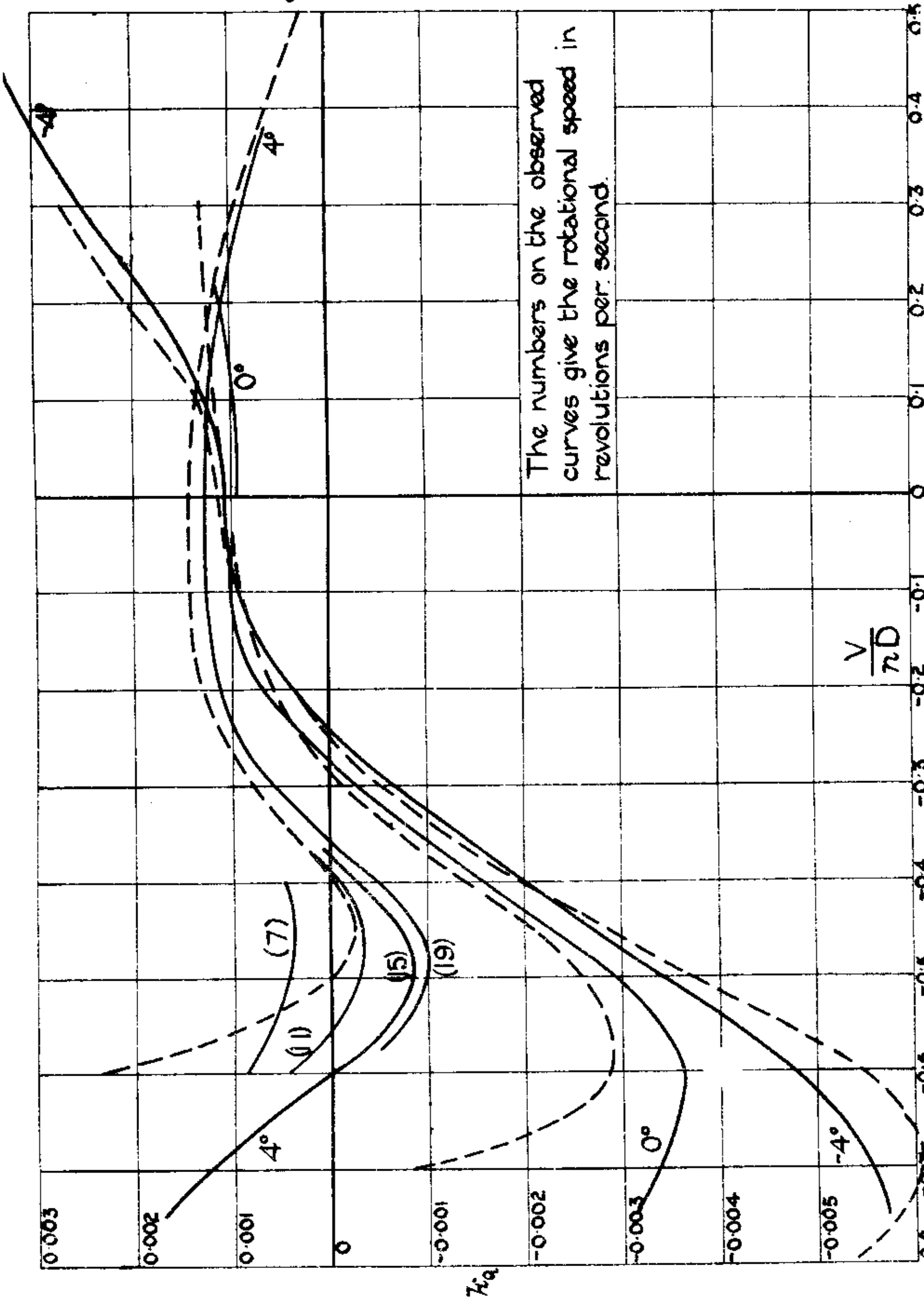
R.&M.1014.

Airscrew of Aerofoils. Torque Curves. FIG. 7.

Calculated Curves - - - - -

Observed " ————

Blade angles shown on curves.



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R.&M. 1014.

Airscrew of Aerofoils. FIG. 8.

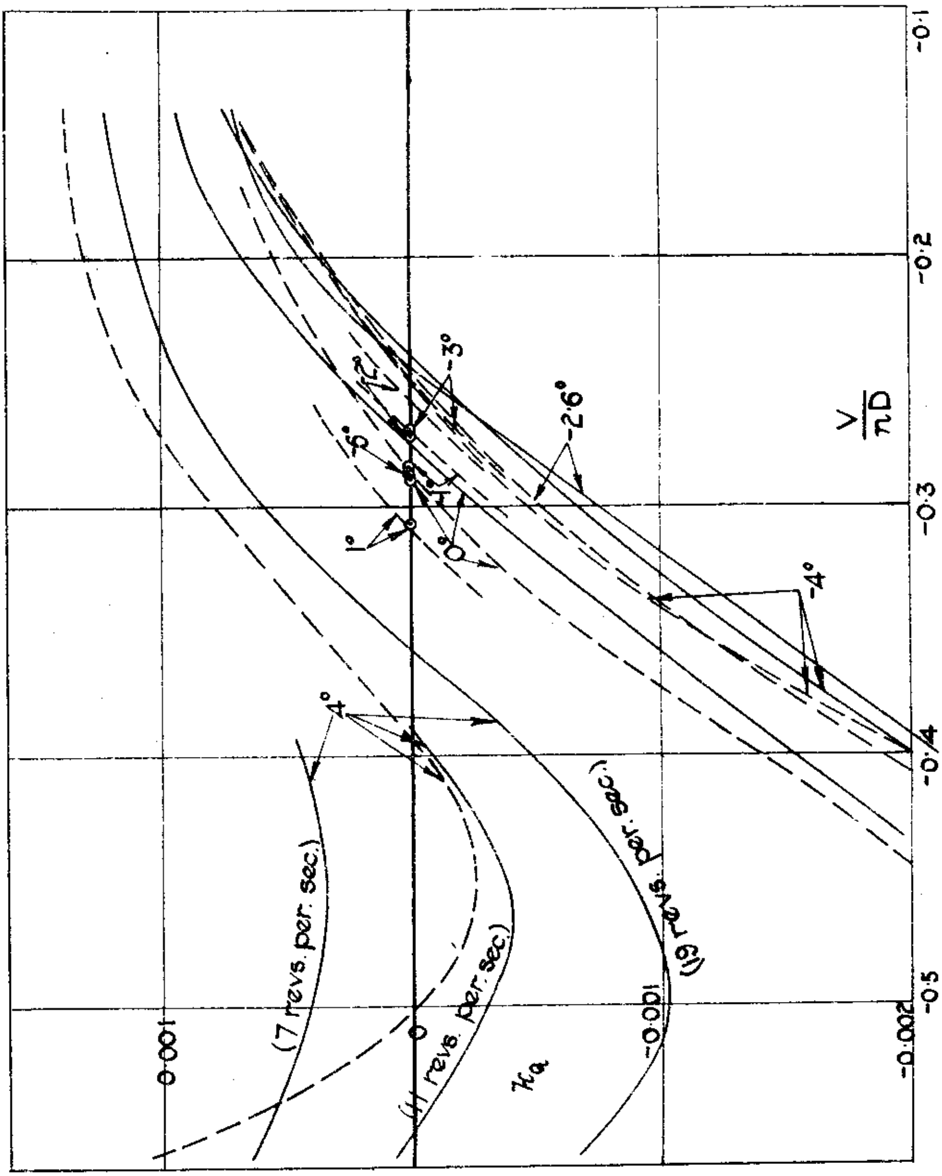
Torque Curves in the neighbourhood of zero torque.

Calculated Curves - - - - - -

Observed " ————

Observations on ball bearings ⊙

Blade angles shown on curves.



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R.&M.1014.

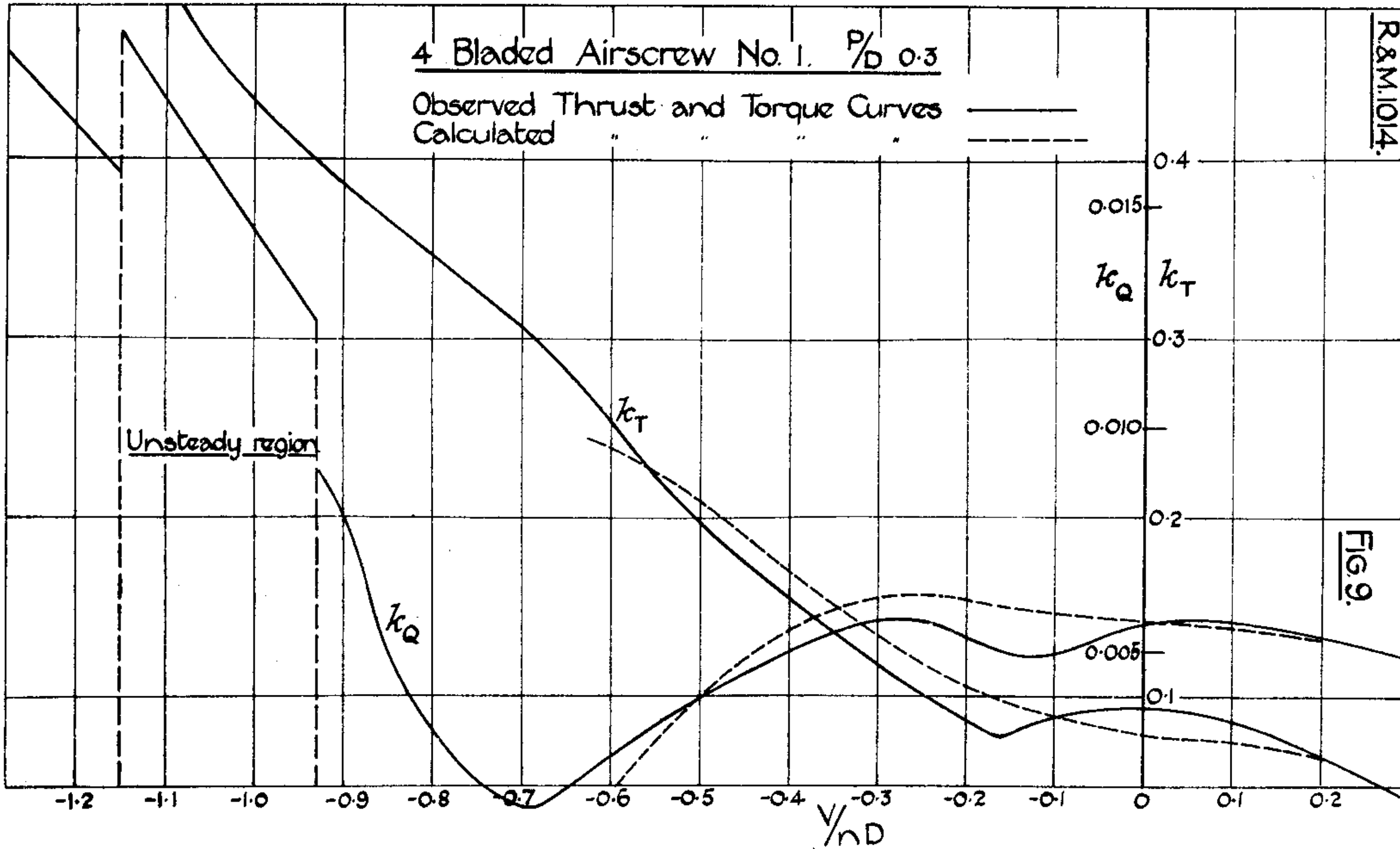
4 Bladed Airscrew No. 1. P/D 0·3
Observed Thrust and Torque Curves
Calculated " " " "
Unsteady region
k_T
k_Q
0·4
0·3
0·2
0·1
0·015
0·010
0·005
-1·2
-1·1
-1·0
-0·9
-0·8
-0·7
-0·6
-0·5
-0·4
-0·3
-0·2
-0·1
0
0·1
0·2
V/nD

FIG. 9.

FIG. 10.

Observed velocities 1 foot from Tunnel Wall (all screws) and velocities in plane of screw calculated by formula 10·01.

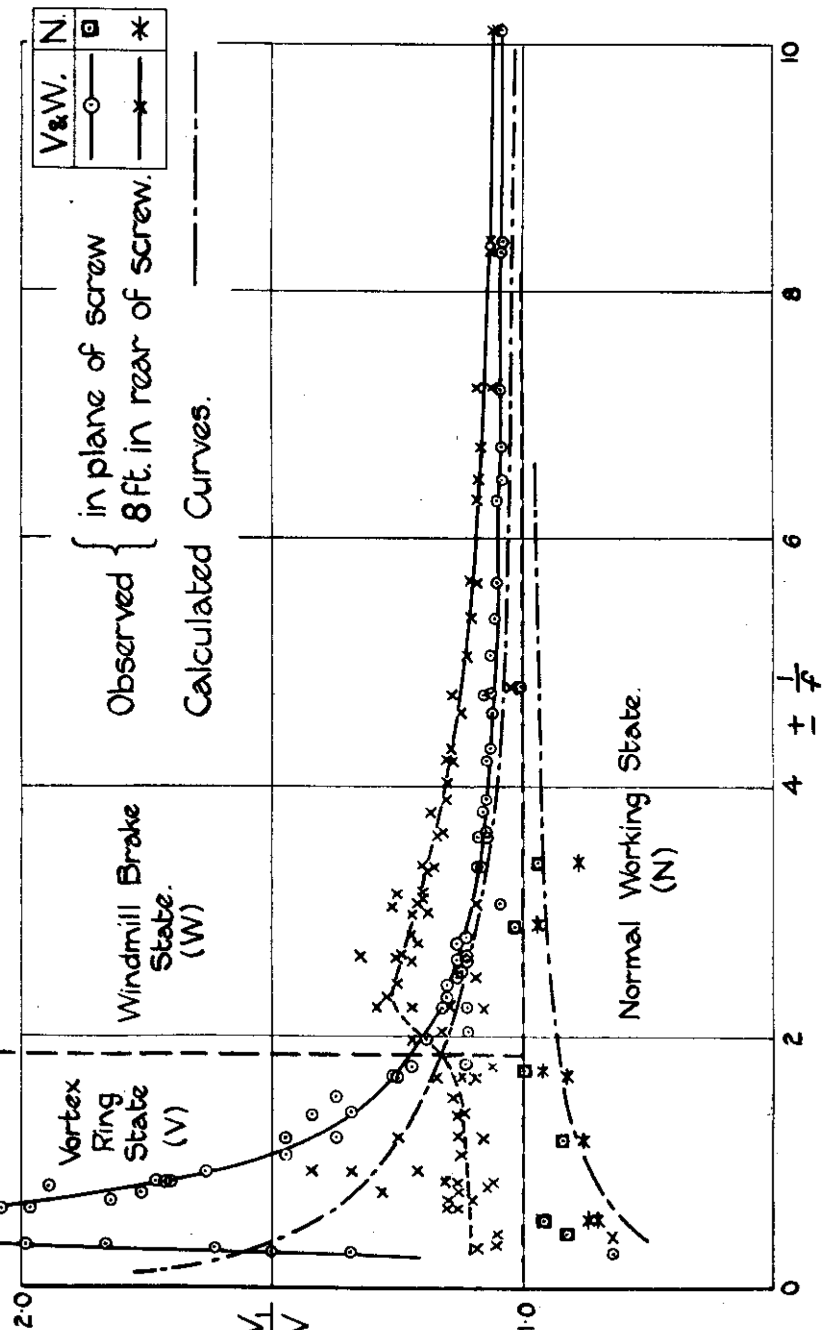

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TABLE 8—*continued.*

Observed velocities (V_1/V).

(*d*) Airscrew of Aerofoils. Blade angle (measured from under-surface) = $-2\cdot6°$.

$\frac{1}{f}$	V_1/V		Working condition
	In plane of screw	8 ft. in rear of screw	
4·30	1·06	1·14	W
3·63	1·07	1·16	,,
3·10	1·09	1·20	,,
2·62	1·13	1·25	,,
2·04	1·11	1·16	,,
1·69	1·11	1·11	,,
−1·77	1·11	1·06	,,
−2·23	{1·11	{1·08	,,
	{1·15	{1·29	,,
−2·64	1·12	1·32	,,
−3·03	1·10	1·26	,,
−3·80	1·08	1·18	,,
−5·65	1·05	1·10	,,

(*e*) Airscrew of Aerofoils. Blade angle (measured from under-surface) = $-4°$.

$\frac{1}{f}$	V_1/V		Working condition
	In plane of screw	8 ft. in rear of screw	
10·09	1·04	1·06	W
8·41	1·04	1·06	,,
7·21	1·05	1·09	,,
6·31	1·05	1·09	,,
5·61	1·05	1·09	,,
5·05	1·06	1·11	,,
4·79	1·00	1·02	,,
4·75	1·06	1·13	,,
4·59	1·06	1·12	,,
4·03	1·06	1·15	,,
3·89	1·07	1·15	,,
3·60	1·07	1·17	,,
3·29	1·08	1·19	,,
3·14	1·10	1·25	,,

TABLE 9.

Measured dimensions of the blade section of airscrew of aerofoils.
(Undersurface flat.)

$x =$ (distance from Leading Edge) $\div$ (chord).
$y =$ (height of upper surface) $\div$ (chord).

x	y	x	y
0	0	0·30	0·0609
0·02	$0{\cdot}0218_5$	0·40	0·0590
0·04	0·0304	0·50	0·0544
0·06	0·0370	0·60	0·0478
0·08	0·0423	0·70	0·0388
0·12	0·0499	0·80	0·0280
0·16	0·0548	0·90	0·0153
0·20	0·0578	0·98	0·0035
0·24	0·0598	1·00	0